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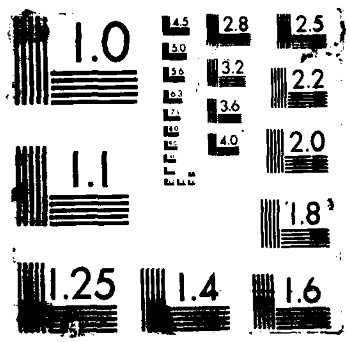
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IDA PAPER P-2064

DECISION SUPPORT REQUIREMENTS IN A UNIFIED LIFE CYCLE ENGINEERING (ULCE) ENVIRONMENT

Volume I: AN EVALUATION OF POTENTIAL RESEARCH DIRECTIONS

AD-A195 752

ULCE DSS Working Group

May 1988

Prepared for
Office of the Under Secretary of Defense of Acquisition
(Research and Advanced Technology)

Supported by
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Wright-Patterson AFB, Ohio

IDA

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This paper has been reviewed by IDA to assure that it meets high standards of thoroughness, objectivity, and sound analytical methodology and that the conclusions stem from the methodology.

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The goal of Unified Life Cycle Engineering is to develop an advanced design environment that allows considerations of producibility and supportability to be integrated into the design process in a timely fashion, i.e., early in the design process, along with the usual considerations of performance, cost, and schedule. A key factor in being able to develop an ULCE design environment is the management of the design decision-making process in such a way as to ensure that designs, optimized among all the competing factors, both up front and downstream, can be produced. This report is the result of a study addressing the design decision support problem under ULCE.

Volume I contains the results of the ULCE DSS Working Group efforts to outline a research and development plan for the design decision support for ULCE. Volume II is a review of the optimization techniques currently used or proposed to aid in the decision processes involved with competing requirements. The third volume of the report applies some of these optimization methods and other decision support techniques to actual design problems.

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DECISION SUPPORT REQUIREMENTS IN A UNIFIED LIFE CYCLE ENGINEERING (ULCE) ENVIRONMENT

Volume I: AN EVALUATION OF POTENTIAL RESEARCH DIRECTIONS

ULCE DSS Working Group

May 1988

IDA

INSTITUTE FOR DEFENSE ANALYSES

Contract MDA 903 84 C 0031
Task T-D6-489

PREFACE

This report was prepared by the Institute for Defense Analyses (IDA) for the Office of the Under Secretary of Defense for Acquisition and the Air Force Human Resources Laboratory under contract number MDA 903 85 C 0031, Task Order T-D6-489, Decision Support Requirements - ULCE.

The issurance of this report meets the specific tasks of "[identifying] conceptual approaches to optimization among competing design requirements, [identifying] fertile areas of research which address the problems of design optimization and trade-offs in an ULCE environment, [and preparing] a plan for future research."

This report was reviewed by Drs. Jeffrey H. Grotte and Robert I. Winner of IDA and by Dr. Edison Tse of Stanford University.

ACKNOWLEDGMENTS

Volume I of this report is a product of the DSS Working Group. Their names and addresses are given in Appendix A of this document. The Working Group information has been compiled by William Cralley and David Owen of IDA. Section I of this volume was written by Professor Robert Kuenne.

CONTENTS

Appendices

ACRONYMS AND ABBREVIATIONS

DSS	Decision Support System
EDIF	Electronic Design Interchange Format
IDA	Institute for Defense Analyses
IGES	International Graphics Exchange Specification
Ilities	Those attributes of a product that in totality are measures of effectiveness or of fitness of use for accomplishing desired objectives
MAUT	Multiattribute Utility Theory
MIT	Massachusetts Institute of Technology
MOE	Measure of Effectiveness
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
RPI	Renssalear Polytechnic Institute
SE	System Engineering
SEMG	System Engineering Management Guide
ULCE	Unified Life Cycle Engineering
USAF	United States Air Force

EXECUTIVE SUMMARY

In the summer of 1985, a comprehensive study to identify new technologies with the potential of high payoffs in warfighting capabilities was initiated by the Secretary of the Air Force and the Air Force Chief of Staff [Ref. 1]. This study, Project Forecast II, identified Unified Life Cycle Engineering (ULCE) as a major thrust area with significant promise for improving force readiness and combat capability. The goal of Unified Life Cycle Engineering is to develop an advanced design environment that allows considerations of producibility and supportability to be integrated into the design process in a timely fashion, i.e. early in the design process, along with the usual considerations of performance, cost, and schedule. A key factor in being able to develop an ULCE design environment is the management of the design decision-making process in such a way so as to ensure that designs, optimized among all the competing factors, both up front and downstream, can be produced.

With a view toward defining the decision support problems, which must be addressed under ULCE, and developing a comprehensive Research and Development program to address these problems, the Air Force Human Resources Laboratory and the Office of the Deputy Under Secretary of Defense (Research and Advanced Technology) tasked the Institute for Defense Analyses to conduct a study addressing the design decision support problem under ULCE. Specific tasks to be undertaken included identifying conceptual approaches to design decision support and optimization, analyzing these approaches for their applicability to ULCE, and developing a plan identifying priority areas for future R&D needed to support implementation of an ULCE design decision support system.

This report on Decision Support Systems (DSS) for ULCE is organized into three volumes. Volume I contains the results of the ULCE DSS Working Group efforts to outline a research and development plan for the design decision support for ULCE. Volume II is a review of the optimization techniques currently used or proposed to aid in the decision processes involved with competing design requirements. The third volume of the report applies some of these optimization methods and other decision support techniques to actual design problems.

The first volume of the report is a research prospectus that resulted from the interactions among a variety of researchers in Academia, Industry, and Government, who were assembled by IDA into the ULCE DSS Working Group. The members of this group participated in two meetings and contributed a number of papers on research issues for decision support in ULCE, which are contained in the appendices to Volume I. The areas of research are presented below in priority order; they were felt to be the important areas for a concentrated research effort by a strong consensus of the members of the group.

The research area given the highest priority by the working group is an ULCE-supported decomposition of the design process and its integration with systems engineering. This research will require a formal application of systems engineering techniques to the design process, with a concentration on the flow of information at the vertical and the horizontal interfaces of the hierarchical structure of the design process.

The second priority item is research into the techniques for quantifying the qualitative factors in design and incorporating those qualitative attributes in ULCE. The identification of the components that enter into the quality design factors and the development of measurement techniques for these factors are seen as difficult tasks that will require a concentrated research effort.

Priority #3 is the development of optimization and arbitration support procedures in decision support systems applicable to ULCE. Initial attention should be given to a multi-objective optimization approach, which converts all but one of the objectives into constraints. Sensitivity analysis techniques for analyzing trade-offs between objectives through alternating which objectives are converted are important research items for the multi-objective optimizations encountered in the ULCE process. The fourth priority was given to an investigation of the issues surrounding the critical decision support systems implementation technologies and the interfaces with other ULCE components. A critical examination of advanced data base technology, data base management systems, and graphic display requirements will be required.

The second volume is the result of the research of Dr. Shapour Azarm, Mr. Joseph Naft, and Dr. Michael Pecht of the University of Maryland into various conceptual approaches to optimization. The optimization problem is one of maximizing (or minimizing) one or more objective functions (criteria) of the design variables subject to various constraints defined for those variables. Classical derivative-based methods, methods for unconstrained problems, methods for linearly and nonlinearly constrained problems, mathematical techniques, and artificial-intelligence-related techniques are covered. An appendix is included that details a coupled algorithmic-heuristic optimization technique proposed by Drs. Azarm and Pecht. This volume also includes descriptions of the various optimization software packages currently available and prescribes a process for selecting and evaluating a specific optimization technique. An extensive bibliography on optimization is included.

The results of the investigation into the various optimization techniques led the researchers at the University of Maryland to target decomposition-based optimization and other methods that can handle the hierarchical systems associated with engineering design as areas where future research is needed. Although many mathematical optimization techniques exist, their applicability to the engineering design process for ULCE is questionable, largely due to the qualitative nature of many of the design goals, requirements, and criteria. Also, trade-off studies and their corresponding sensitivity analyses that correspond to variations in the design parameters or assumptions often are more important to the design process for real systems than is the optimal solution itself. These issues also are voiced by the DSS working group in Volume I of this report.

Volume III also is largely based on research supplied by the University of Maryland group given above. It begins with a review of strategies and techniques used in decision support, including functional and physical block diagram modeling, multi-goal modeling, cooperative life cycle design, and the use of knowledge-based design assistants. System-level optimization, which is first discussed in Volume II, is further expanded and an appendix gives a detailed two-level decomposition optimization technique, developed by Dr. Azarm, that utilizes a global monotonicity analysis for the first level subproblems and any conventional nonlinearly constrained optimization technique for the second level problem.

Volume III continues with the application of various optimization techniques as analytical tools in the design of printed wiring boards for maximum reliability. The design problems considered include optimal component redundancy determination for reliability and component placement for optimum reliability and routability for both convection-cooled and conduction-cooled boards. A sequential quadratic programming optimization technique was used for the component redundancy determination, and a sensitivity analysis relating to the board area was conducted. A feasible, though not necessarily optimal, solution for the placement problem was obtained using a modified force-directed method and a priority numbering scheme. This method differs from existing heuristic methods of placement for reliability because it addresses the physics of the problem without a methodical guessing procedure for better placement configurations. The results of computer simulations, which verify the applicability of the methods developed, and the detailed equations are included in appendices at the end of Volume III.

An analysis using a discrete data numerical analysis search technique to determine the optimum distribution of coolant flow in an assembly of printed wiring boards also is presented in Volume III. This optimization routine and the multi-goal modeling decision support technique were implemented in software that was given to the Air Force Human Resources Laboratory as part of the decision support system task. The software package, the University of Maryland Computer-Aided Life Cycle Engineering (CALCE) program, is a decision support tool prototype for the competing design goals of reliability (mean time to failure) and cost.

Volume III concludes with a section, written by Mr. David Dierolf of the Institute for Defense Analyses, on the application of artificial intelligence techniques to design. This section includes samples of AI Design Systems currently in use for air cylinder design, bridge design, and electronic circuits. An extensive bibliography of AI in design is included in Appendix H of Volume III.

I. WORKING GROUP EVALUATION OF RESEARCH DIRECTIVES

A. INTRODUCTION

1. Approach

Unified Life Cycle Engineering, is multidisciplinary by nature. A successful ULCE system will reflect the considerations of design engineers, engineering technologists from a variety of areas, computer scientists, operations researchers, economists and cost analysts, and human factors specialists. IDA determined that the best way to assess the R&D requirements for design-decision support in an ULCE environment would be to assemble a multidisciplinary group of individuals from Industry, Academia, and Government into a working group who would address relevant, decision-support capability questions and develop a balanced plan identifying critical R&D areas. While it is recognized that in any group various points of view will be held and individuals will often seek to advance their own causes, it was believed that under proper conditions of group interaction and control a consensus could be achieved by a group where no one individual's views were dominant and where a reasonable measure of objectivity could be obtained in the resulting plan. The potential benefits from the interactions of a group having a diversity of viewpoints and backgrounds were believed to outweigh any potential adverse characteristics of such group activities.

Therefore, early in 1987, IDA personnel began to make visits and hold discussions with a variety of persons in Industry, Academia, and Government who might become members of the working group and who were involved in research activities that were closely related to the goals of ULCE. By late March 1987, a group of individuals who were willing to participate in the Working Group had been identified. These individuals are listed in Appendix A. The group was officially termed the ULCE Decision Support System (DSS) Working Group, and the first meeting was set for April 21, 1987 at IDA. As shown in Appendix A, the group achieved a balance of representation from Industry, Academia, and Government.

2. R&D Plan Development Strategy

The strategy employed in developing the plan consisted of holding two working group meetings and a final plan development meeting by IDA members in the group. The agendas for the working group meetings are contained in Appendix B.

The first working group meeting lasted one day and had as its goals the development of an overall framework for plan development, definition of the scope of ULCE as related to DSS requirements, and development of an initial list of R&D areas for consideration in the plan. At the conclusion of the first meeting, volunteers were solicited to write white papers on these R&D areas for presentation and discussion at the follow-on meeting. The members were requested to work on these papers and give further thought to what had transpired at the first meeting and during the period between meetings. As an aid to this process, minutes of the first meeting were prepared and sent to all members shortly after its adjournment.

The follow-on meeting was held at IDA on May 19-20, 1987. On the first day of this meeting, those members of the group who had prepared papers presented them to the group. (These papers are contained in Section II.) Discussions were held after each presentation. At the end of the day, the members were asked to consider what had transpired during the day and to develop a prioritized list of R&D topics based on their perceptions of which areas were most critical in development of an ULCE DSS capability.

These prioritized lists were presented by each member of the group the following morning. After these presentations, there was considerable discussion among group members. This discussion led to developing a strong consensus among the group members regarding the highest priority areas which needed further research.

After the follow-on meeting was adjourned, IDA members of the working group collected all the information that had been developed during the meeting and summarized and organized it. The research prospectus contained in Section B was developed based on this information. Also, minutes of the follow-on meeting were also prepared for distribution to each group member.

3. Acknowledgments

IDA would like to thank all the members of the working group for the significant amount of time and effort they extended to prepare for and attend the meetings and to write the white papers that are contained in this report. Special thanks are due to the following companies and government agencies for allowing their personnel to participate in the working group effort:

Boeing Aerospace Company

Boeing Computer Services

Lockheed-Georgia Company

Hughes Aircraft Company

The National Science Foundation

The Air Force Office of Scientific Research

The IDA Study team also would like to thank Colonel Donald Tetmeyer, Director of the Logistics and Human Factors Division of the Air Force Human Resources Laboratory, for delivering a thought-provoking keynote address to the first group meeting. This address helped to set the course for both group sessions.

B. RESEARCH PROSPECTUS

Unified Life Cycle Engineering (ULCE) is a systems concept that's goal is the integration of all relevant characteristics of a product at each stage of its life cycle. Its intent is to move throughout the product's time sequence in an anticipatory manner to identify and incorporate solutions and to foresee problems before they arise. Its mode, therefore, is to strike compromises in product design among such concerns as performance, cost, maintainability, durability, producibility, modularity, and so forth. Ideally, ULCE strives to achieve the "optimal" product design defined as the "optimal" compromise among the many desirable properties over all stages of its life cycle. Practically, it seeks systemic approaches to "very good" designs in this same sense.

As a concept applied to weapon system design, ULCE seeks to unify the design, testing, production, and fielding phases of such equipment so that performance, cost, scheduling, producibility, and supportability parameters of design candidates can be determined prospectively and used to condition design choices. Hence, it is implied that the ultimate (optimal) design choice will be the result of arbitration and negotiation by a team of design engineers, production engineers, logistics specialists, reliability engineers, costing personnel, etc., who are supported by useful data bases, optimization programs, networking systems, and similar computerization. One of the software components of this interactive (DSS); and its development is a precondition for an operational ULCE.

This research prospectus focuses on the development of the DSS by discerning through consensus which components are believed to require substantial research effort, by prioritizing those suggested tasks, and by rationalizing these recommendations by indicating the potential payoffs in this research program.

To assist in the integration of the suggested research plan for DSS, helpful overview of ULCE as a decision process is presented. To fix ideas, this overview will be presented within the context of aircraft design. In no sense is the presentation meant to be prototypical. It is to be used simply as a convenient analytical framework, to organize the presentation of the suggested research plan, and to give it perspective.

1. ULCE as a Hierarchical System

The structure of an aircraft design system may be viewed as a hierarchy of horizontal layers of decision making which ranges from top to bottom in ascending order of design detail and is integrated vertically by interfaces between the layers. ULCE, therefore, must seek to compromise the competing demands of the claimant agencies at each horizontal layer of the hierarchy and at the same time condition those optimizing procedures by the vertical flow of information through the interfaces between higher and lower tiers of the hierarchy. In short, ULCE, as a total system integrator, must focus on the problems of vertical information flow through horizontal decision processes with the goal of improving the emerging design.

In Figure I-1, an abbreviated schematic diagram of these integration tasks for a military aircraft is presented. The first level of the hierarchy requires that the basic categories of the aircraft structure be considered in a coordinated fashion as a first iteration to obtain an initial basic design. This set of parameters flows downward to the second level of design activities which initiate designs for various assemblies after compromising among their own needs. The second tier then passes the parameters down to the next horizontal level for the design of supporting subassemblies and/or sends information to the higher level communicating problems encountered or suggestions for improvement. This may lead to a second iteration of basic design with necessary redesign of assemblies and subassemblies. The efficient flow of information upward and downward through the

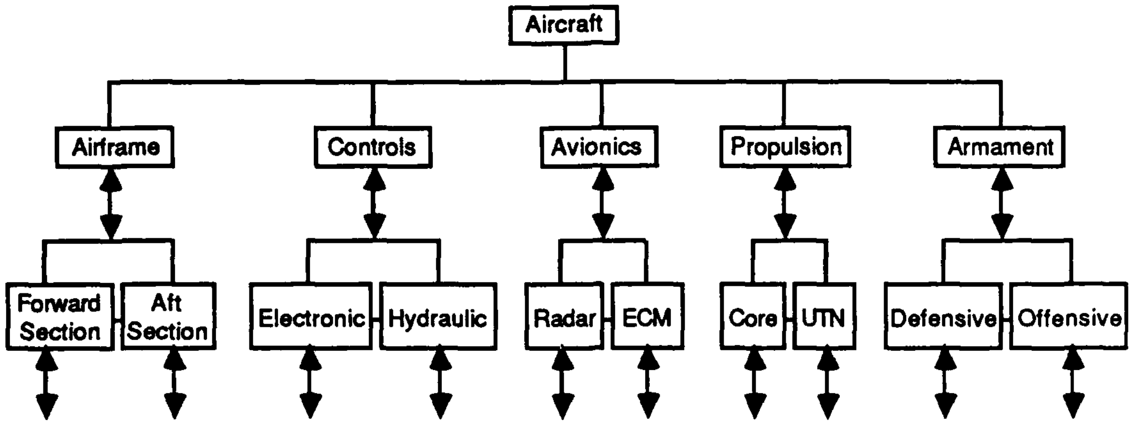


Figure I-1. Schematic Representation of Horizontal and Vertical Integration Problems in Aircraft Design

interfaces and the optimal usage of that information at the horizontal levels constitute the goals of ULCE. The primary task of ULCE at the horizontal levels in an extended sense, may be termed that of *optimization* . The concerns of ULCE, with these vertical interfaces, may be viewed as the *systems analysis* problems.

The areas and topics of proposed research for DSS as they relate to this framework are the following:

- Obtaining conceptualizations of the design process that conform more closely with the aims of ULCE and its DSS
- Developing optimization techniques and supporting methodologies that improve the horizontal negotiating processes
- Implementing techniques to facilitate the vertical flow of necessary information through the interfaces to support the horizontal processes
- Developing computer implements in the form of data bases, human interface software, and interfaces for DSS with the remainder of ULCE.

A description of the suggested research areas in greater detail and their prioritization are given in the sections that follow.

2. Priorities

a. ULCE-Supportive Decomposition of the Design Process and its Integration with Systems Engineering

One of the important preconditions for DSS strategy formulation is to devise a decomposition of the design process that best agrees with the goals of ULCE. While this decomposition should clearly be related to the current organization structures of defense contractors, it must also facilitate the enhanced interchange implied by ULCE at horizontal decision levels and must integrate the systems engineering aspects of the design process at the vertical interfaces.

What is the optimal decomposition that will introduce the *ilities* effectively into the design process? Should the horizontal levels be determined by structural component (Figure 1: Airframe, Controls, Avionics, Propulsion and Armanent) or by the degree of interdependence of design-decision parameters among tasks (avionics system design, computer design, integrated circuit design)? Information must flow across the horizontal strata and up and down the vertical structure through interfaces. What are the implications for information flow in both dimensions of the various decomposition alternatives? What is the nature of the filtering process on vertical information flow in the alternative decompositions that will avert a flooding of the system?

The ULCE process so viewed is one of iterative design adjustment as requirements flow downward through the structure and responses flow upward to modify prior decisions. How do the alternative decomposition structures affect the rate of convergence of the process and the duration of the design cycle? How well do they conform to the natural sequencing of such decisions? What are their implications for cost and resource needs?

It is concluded that research into the design of a DSS for ULCE depends upon well-reasoned answers to such structural questions. ULCE must operate within a framework that conforms to its needs for complex interdependence horizontally and vertically without overburdening the decision process with worthless information interchange and excessively multilayered authority. Therefore, ULCE must shape a DSS but also be affected by the practical concerns of a DSS. The fundamental nature of the questions raised by this mutual dependence explains the high priority that should be given this research.

Specific problems that should receive explicit attention within this research area are the following:

- Determine the extent to which there are generalizable or generic characteristics of information flow at the vertical interfaces that recur at most levels and for most assemblies or components.
- Formalize application of systems analysis techniques to the problems of decomposing the design process, with special regard to changes caused by special characteristics of assemblies or components.
- Investigate the degree that the ULCE system must correspond in its design, one-to-one, with the product being designed. To what extent is ULCE--and therefore its DSS--product specific?
- Characterize the information required to flow through the vertical interfaces to the next highest tier. This feedback information should not burden data transmission and analyses with comprehensive design information, but, rather, it should be limited to that subset relevant to design modifications. How does the content of this information differ by level in the decomposition?
- Determine how the content of this information flow differs among phases of the design process--concept exploration, demonstration and validation, full scale development, production, and deployment. What are the sources--formal and informal--of this information at the various phases?

b. Quantifying the Qualitative Factors in Design and Incorporating Attributes in ULCE

The second priority in the design of a ULCE, DSS research program is a search for methods to incorporate the qualitative factors of the design process into the formal and informal optimization procedures contemplated for ULCE. For example, many components of the concepts of producibility and supportability are qualitative attributes whose potential for formal inclusion in DSS depends upon the ability to quantify them.

The mathematical theory of measurement prescribes certain strict requirements that must be met by the measurement functions before their exact degree of uniqueness can be established. That uniqueness level determines the formal legitimacy or illegitimacy of performing arithmetic operations on their values. It is certain that many qualitative attributes relevant to ULCE will not be capable of exact measurement in the sense that no firm assignment of uniqueness characteristics will be possible for any functional assignment of numbers to those attributes.

Nevertheless, based upon the subjective judgment, intuition, and experience of experts, the use of such inexact scalings of attributes abounds in many fields. It is urged that research be conducted in scaling methods and other inexact measurement techniques for attributes within the ULCE context in order to provide a basis for DSS. Most notably, scaling of the *ilities* should receive a high research priority.

The ultimate validation of such measurement procedures rests wholly upon empirical demonstration of their *consistency*--different groups of experts randomly selected arrive at similar scalings--and their *usefulness* in decision making. Therefore, testing of such measures in ULCE tasks should be regarded as an essential part of the research.

The measurement of qualitative design factors--and, expressly, the *ilities*--involves four tasks.

1. The first is to identify the component factors that enter into the quality. For example, supportability would incorporate such factors as mean time between failure (an exact measurement), modularity, difficulty of repair, diagnostic complexity, logistic burdens, shelf life, equipment ruggedness, and so forth.
2. The second task would be to devise inexact measurement techniques for those factors that are qualitative. One widely used technique is to ask experts to scale an attribute of a design candidate between 0 and 100, where 100 is given as some well-defined "ideal" design with respect to that attribute and 0 is defined explicitly as an "anti-ideal" design value. An aggregate scaling value (a dimensionless number) may be obtained in a variety of manners of isolating a central tendency from the distribution of answers. Other techniques should be researched, and the specific concerns of scaling techniques as they relate to design factors should be investigated.
3. With the derivation of scale measures of the qualitative factors and the normalization of quantitative factor measurements between 0 and 100, the measurement process to this point will have yielded a set of component factor, dimensionless numbers in the interval [0,100]. The next step is to derive the *relative weights* that should be accorded the factors in the aggregative measurement process (for example, supportability). This process also requires expert judgment. Research into good methods of deriving normalized weights within the ULCE context should be undertaken. Cross-factor analysis and Saaty's eigenvalue prioritization method are the most prominent of these methods. Experience has shown that experts are most comfortable with methods that are based on pairwise comparisons of alternatives rather than wider ranging comparisons and these two methods are so grounded. However, in the design process, other methods may prove workable and should be researched. The final result of the procedure will be a set of dimensionless weights normalized to the sum of 1.
4. The remaining task is the combination of the weighted component factors into an index (for example, supportability) for every design candidate. This is usually done by simply summing the weighted component factor scalings. More complicated aggregation methods (for example, taking geometric means of the weighted scalings) may be studied.

The derivation of *attribute weights* in step 3 above should be complemented by research into computation of *discriminatory weights* for component factors that incorporate the capacity for them to contribute meaningfully to the choice among design candidates. For example, diagnostic complexity may be judged by the experts to be weighted extremely high in supportability, but if all design candidates have about the same scaling value this factor will not contribute to the choice of a design. The importance of the total weight to be given this factor should include both attribute weight and discriminatory weight. One method of determining discriminatory weight is by an entropy measure, and the potential of this method in an ULCE environment should be researched.

It is suggested that initial emphasis in the research be placed on the following topics:

- Cross-factor analysis by pairwise comparisons of component-factors' attribute importance is a simple procedure that economizes experts' time and patience. Results of such analysis vary somewhat because of alternative manners of normalizing responses. The simplicity and economy of the method recommend extensive experimentation with it initially, together with testing of various normalization procedures.
- The distinction between attribute weights and discriminatory weights is expected to be important in measuring the effect of component factors upon the design *decision* process. This is because candidate designs for weapon systems may be expected to be similar to many component factors which are deemed important as attributes. Entropy measures of discriminatory weights afford a simple approach to the problem, and extensive experimentation with them is recommended.
- At the stage of negotiation and arbitration among design candidates in the negotiation set, the formalization of expert preferences among the candidates and the interpersonal comparison of such preferences become important. These problems are difficult to resolve in theory and the derivation of empirically workable methodologies should be given much attention.
- In the recommended procedures for scaling presented above, it is important that all subjects have similar conceptions of 0 and 100 anchor points in the calibration. The discussion above used the notions of "ideal design" value of a component factor and "anti-ideal design" value to obtain these values by consensus. The determination of these points by experimentation in the ULCE context should be researched.

c. Optimization/Arbitration Support Procedures in DSS

The working group unanimously concluded that, in the last analysis, optimization techniques in DSS must be designed to guide and assist experts in an interactive way in choosing designs that reflect the experience, judgment, and intuition of the experts. Optimization techniques must not be designed to provide *the* answer. Rather, they should aim at isolating efficient design candidate sets that provide a negotiation set to help focus the experts' evaluations; aiding the arbitration process that serves to choose an optimum solution from a negotiation set; suggesting compromise designs that come closest to some consensual ideal-but-infeasible design; and providing trade-offs between design factors to help define the limits within which negotiation can proceed.

With this in mind, a dominant characteristic of the complex design process should guide the research into optimization procedures for a DSS. That characteristic is the multiplicity of objectives sought in weapon systems design. Rarely can any single objective be chosen as an exclusive criterion variable, but almost always ideal compromises among a set of criteria must be sought. Multiobjective optimization techniques--such as methods that convert objectives into constraints, goal programming, compromise programming, and multiobjective linear programming--are suggested as candidates for researching their ULCE potential.

One method for converting multiple objectives into a single objective function is the multiattribute utility theory. This theory seeks to decompose multiargument utility or preference functions into their components in ways that maintain their consistency with the components and preserve the certain, desirable measurement-uniqueness characteristics discussed in Section b. Some effort should be devoted to discerning the potential usefulness of multiattribute utility theory for ULCE.

Once negotiation sets have been isolated for the consideration of expert panels, optimization support shifts to aiding the group process of arbitration among design candidates in the final selection. The multiattribute utility theory, or a simpler derivation of group preferences, may be useful at this stage and should be researched. More generally, the study of group-dynamic techniques as developed by organization theorists and psychologists, may prove helpful in supporting this cooperative decision process.

The initial conceptualization of the ULCE and DSS decision processes suggest the following topics for intensive research effort.

- The multiobjective optimization approach that converts all but one objective function to constraints has strong initial appeal for ULCE's problems. It is capable of handling nonlinear objective and constraint functions that arise frequently in weapon systems design. Penalty-function algorithms have an established record of solving such problems efficiently, and recent improvements in these algorithms promise even greater solution efficiency. The methodology accords well with the need to isolate negotiation sets of design candidates, since various solutions can be obtained by (1) alternating objectives in the objective function--constraint function positions, and (2) sensitivity analyses. Moreover, trade-offs between objectives can be readily obtained through the methodology. It is recommended that this approach receive initial attention in research directed at development of optimization techniques.
- Compromise programming seeks to isolate sets of feasible designs that are at minimal distances from one or more ideal-but-infeasible designs when those distances are measured by various weighted Minkowski metrics,

$$M_p = [\Sigma_i (x_i - x_i^*)^p]^{1/p}$$

(where $x^* = [x_1^*, x_2^*, \ldots, x_n^*]$ is the ideal design, and $p>0$).

This method also can be used in nonlinear contexts. By its very nature, it reflects the notion of weapon system design as a series of compromises. It also deserves an initial research effort within the ULCE context.

- When approaching optimization problems in a particular application, the extent to which certain functions can be approximated by linear or piecewise linear forms is always uncertain. If these approximations are possible, huge advantages arise in computational efficiency. Optimization experts are skilled in discerning these opportunities, and it is recommended that research efforts include consultation with such personnel.
- The working group is somewhat skeptical of employing the multiattribute utility theory to the problems of preference specification in ULCE. Nonetheless, if it can be demonstrated that these methods can be useful and cost efficient, they can aid the optimization process considerably. Initial research should explore these possibilities, but a decision concerning their usefulness should be made quickly in order to conserve the research budget.

d. Critical DSS Implementation Technologies and Interfaces with other ULCE Components

A final omnibus category of importance for research concerns an important group of supporting functions that are necessary for DSS activities and that provide or facilitate DSS interfaces with other ULCE activities.

Central to those functions that are directly supportive of DSS and to the design of necessary data bases are the problems of modeling the flow of information through the vertical interfaces of the design structure and the consideration of the essential properties of design modifications that condition the flow of information. Carefully defining the data bases that are necessary for DSS and the required structures for these data bases are of obvious importance to their efficient functioning. Less apparent, perhaps, is the importance of carefully designing the information flow through the horizontal decision layers and vertical interfaces of the system. What data should be available to decision makers in various layers and how can it be protected against alteration and contamination? What principles of filtering at the interfaces will preserve efficient information interchanges but prevent system overburden? How can configuration management and change control capabilities be properly integrated into the ULCE design decision support structure? Answers to such questions depend, most importantly, on the nature of the design process at each horizontal layer of the ULCE structure and on the types of information concerning modifications of design that are important at each level. Extensive research, geared to the specifics of DSS design, should be devoted to these concerns, and research into compatible design specification languages included.

The futility of installing ULCE or DSS systems without careful regard for the human interface with such systems was stressed by several members of the group. Ability to access and employ the systems with user-friendly software is a requirement in order for decision makers to make use of them. Human interfaces must be consistent across diverse ULCE applications and DSS tools. Another desirable feature for the human interface is the ability of the software to determine the user's level of expertise and to present him/her with instructions and guidance pertinent to that level. Techniques have been developed recently by researchers in human-computer interfaces that should be adapted for use in ULCE DSS systems.

Finally, other-than-human interface problems constitute one of the most important hardware/software considerations that will confront ULCE and DSS design. The need for interfaces among different makes of hardware is a difficult problem that must be addressed. Selection of computer languages that are most compatible with various kinds of information flow is another. Research needs to be done to determine the role of data exchange standards, such as IGES and EDIF, and product definition standards, such as PDES within the ULCE context.

Many of the problems that deal with computer implementation and interfacing will be solvable only as the ULCE and DSS programs are better defined. Nonetheless, some broader research effort, which anticipates the problems that are generic at all levels of the ULCE structure and/or that are foreseen to present major barriers to the DSS design, is considered to be worthwhile in reducing cost and completion time.

The broad implementation problems listed below should receive research emphasis in the initial DSS tasks.

- Engineering needs for data-base design must be expected to differ from those that spring from DSS structure. It is important to identify those aspects of DSS data-base design that lead to competition with, contradiction of, or require extension to data bases that are engineering dictated . The advantages and disadvantages of advanced data-base technology, such as object-oriented data bases versus the relational data base structure more commonly used in business Decision Support Systems, must be examined. The role of distributed data base management systems in ULCE must be addressed.
- It is believed that all vertical interfaces in the ULCE structure will reveal certain core information requirements in addition to each interface's specialized needs. This includes a commonality of graphic display requirements. The

identification of this core of critical requirements, relative to the DSS task of providing decision support, is most important.

C. CONCLUSION

The topics included in this research prospectus, as well as their prioritization, were based upon a strong consensus of the members of the working group. They are not meant to be exhaustive, but, rather, the topics were shaped with the desire to move DSS, in its initial phase, in directions which are of unquestionable concern for its ultimate success.

II. WORKING GROUP WHITE PAPERS

This section contains white papers prepared by members of the working group after the first meeting. These papers were presented and discussed at the second meeting. The authors of these papers are as follows:

A. *Measurement Problems in Optimization Support of ULCE*, Professor Robert Kuenne, Princeton University.

B. *Multiobjective Optimization as a Support to ULCE*, Professor Robert Kuenne, Princeton University.

C. *Propagation of Design Changes and Information (Configuration and Change Control Problems)*, Dr. Iman Foroutan and Mr. David Zarnow, Hughes Aircraft Company.

D. *Theory of Measurement (How to Quantify the Ilities)*, Dr. Iman Foroutan, Hughes Aircraft Company.

E. *Decomposition of the Design Process*, Mr. J.E. Rogan, Lockheed-Georgia Company.

F. *Extended Optimization--Quantitative and Qualitative Techniques*, Mr. J.E. Rogan, Lockheed-Georgia Company.

G. *Arbitration and Negotiation Methods Among Competing Design Requirements*, Mr. Joseph Naft, University of Maryland.

H. *Design Advisory Systems*, Mr. Joseph Naft, University of Maryland.

A. MEASUREMENT PROBLEMS IN OPTIMIZATION SUPPORT OF ULCE

A recurring barrier to the application of optimization techniques to product design is the presence of product attributes, expert preferences, and weighting factors that are not measurable within the strict confines of the theory of measurement. Recourse must be made, therefore, to fuzzy methods of quantification which, because of their lack of firm theoretical basis, can only be justified by their empirical usefulness. Their appropriateness, therefore, depends upon the answer to a simple question: does their use result in better answers from a design process that employs them compared with one that does not?

Decision theorists, psychologists, economists, and operations researchers have devoted a great deal of time to the derivation of scalings of this type. If optimization techniques are to be applied successfully to ULCE it is almost certain that fuzzy measures will have to be employed. Some time, therefore, should be spent in researching methods that can be applied in important ULCE areas, and validation testing of such techniques should be conducted within the design context.

This brief, nontechnical paper is an attempt to present the limitations of the theory of measurement in attacking these problems and to present some of the more practical scaling methods that exist. Only a sample of such approaches can be discussed, and these can be presented only in outline form.

1. Measurement in the Strict Sense

Formal measurement of the degree to which an object possesses a given property entails two problems whose solutions imply the proof of two types of theorem.

a. The Representation Problem

This problem is establishing that the empirical relational system, applicable to the given property, possesses a similar structure (is isomorphic or homomorphic) to a relational system defined (practically speaking) on the real number line. The empirical relational system consists of the set of objects and one or more relations among them with respect to the property. For example, let the set of objects be a set of aircraft designs (set A), the property be the weight of the proposed aircraft, and the relation chosen be the binary relation "at least as heavy as" (symbolized "≥"). Then the empirical relational system can be represented by

$E = \{A, \geq\}$.

Assuming that it is possible to judge these aircraft weights, it is then possible to place the objects in descending sequence with aircraft that weigh the same placed in the same group. To *measure* the empirical objects with respect to the property, however, a numerical relational system

$G = \{N, R_1, R_2, \ldots\}$

on the set of real numbers N and employing the indicated relations R_1, must be established, and a function f defined to map the objects in A onto N in a one-to-one (isomorphic), or where f^{-1} is not one-to-one (ties occur) in a homomorphic, manner such that $f(a) \geq f(a')$ if $a \geq a'$, where a and a' are members of the set A.

For the case at hand, the numerical relational system

$G = \{\text{positive integers}, \geq\}$

can be shown to be homomorphic to the objects in A, and

$G = \{\text{positive integers}, >\}$

to be isomorphic to the sequenced groups of like-weight aircraft. Thus, f is defined as a function that assigns integers to the aircraft such that heavier craft get larger numbers than lighter craft and equal-weight aircraft get the same number. The representation problem is solved when the proof that G is isomorphic or homomorphic to E is completed.

b. The Uniqueness Problem

With this proof, a three-tuple [A, G, f] exists which defines a *scale* of measurement characterized by its "uniqueness," which is to specify the number of transformations of f that yield the same measurement that could have been obtained instead of f. More simply, measurement is the assignment of numbers to objects to provide information about the degree to which those objects possess a given property. The function f is derived by operations that solve the representation problem. By using those operations, what other functions might have been obtained which yield the same information that f does? That is, how unique or nonunique is f in providing that information?

The degree of uniqueness of a scale is crucial because it defines the kinds of meaningful arithmetic operations that can be performed upon the numbers derived from the scale. Four degrees of uniqueness may be specified, the last three of which are directly relevant to optimization procedures.

Nominal Measurement

For example, if the desired property to be measured is "identity of the football player," by putting arbitrary numbers on their uniforms and the same numbers with names on score cards, the "measurement" can be accomplished. But there is minimal uniqueness in the assignments: *any* numbers can be attached to *any* player as long as the labeling convention is followed. This is the least unique type of measurement.

Ranking or Ordinal Measurement (Uniqueness Up To a Positive Monotonic Transformation

Suppose four aircraft designs were ranked from heaviest to lightest, and the relations were:

$$a_3 > a_1 = a_4 > a_2 .$$

If the purpose of the measurement were merely to preserve the ranking, the function f could assign the following real numbers to the aircraft:

	$a_3 >$	$a_1 =$	$a_4 >$	a_2
f:	100	6	5	2 .

Following the convention that larger numbers denote weightier aircraft and the same number denotes equal weights, this measurement performs the task of depicting the empirical relational system. However, any other function f* that rises when f rises, falls when f falls, and moves sideways with f (i.e., a positive monotonic transformation of f) yields the same information as f. For example, the following assignments of positive integers will satisfy:

	a_3 >	a_1 =	a_4 >	a_2
f*:	365	150	150	11
f**:	1,000,000	763	763	1 .

Hence, f is unique only up to its transformation by a monotone relation.

Obviously, the increments between the numbers assigned by f, f*, and f** are not meaningful except as to sign. The difference between the numbers assigned to a_3 and a_1

must be positive. It follows, therefore, that arithmetic operations cannot be performed on f, f*, and f** with interpretable results. If added, subtracted, multiplied, or divided the numbers would yield meaningless magnitudes. Hence, this degree of uniqueness (a step up from nominal measurement) is still not sufficient to permit much manipulation. It merely permits preservation of ranking. However, this is frequently sufficient to permit important forms of optimization to be obtained.

Cardinal Measurement of the First Type (Uniqueness Up To a Linear Transformation)

The most widely encountered measurement of this type is the (non-Kelvin) calibration of temperature. In its scaling, there are two degrees of freedom -- an arbitrary origin point and the size of unit of calibration. For example, the origin of the Fahrenheit scale may be taken at the freezing point of water, arbitrarily specified at 32°. The boiling point may be specified at 212°. Implicitly, then, the interval between these two points is divided into 180 equal units or degrees. The Celsius scaling, however, arbitrarily sets the two benchmarks at 0° and 100°, dividing the distance into 100 units.

These are the "same" measurement except for the arbitrary choice of origin and size of unit. The two scales are linear (or affine) transformations of one another. That is, to convert Celsius to Fahrenheit measures, the formula is

$$F^{o} = 32^{o} + 1.8C^{o} ,$$

a linear relationship.

This degree of uniqueness yields meaningful increments: 35° anywhere on the Fahrenheit scale measures the same change in heat and always converts into 19.44° Celsius degrees. It is possible to perform addition, subtraction, multiplication, and division upon measures with this uniqueness and get meaningful results. However, it is not possible to form meaningful ratios. This can be illustrated by comparing the ratio of 70°F/35°F = 2 with its conversion in Celsius degrees, which yields 21.11°C/1.67°C = 12.64, a quite different value.

Cardinal Measurement of the Second Type (Uniqueness Up To a Positive Multiplicative Factor

The distinctive feature of relationships where this type of representation is possible is the existence of a natural origin of zero. Lineal measurement is the familiar example: there is something very compelling about accepting the distance of a point from itself as a natural zero origin. The length of a line may be measured in inches, feet, yards, or meters, but these are all linear transformations of each other with zero origin. If the function f attaches numbers in inches to a length of lumber, then $f^* = 1/12f$ yields feet, $f^{**} = 1/36f$ yields yards, and so forth. Ratios now become meaningful, being the same for all such transformations. This is the most unique form of measurement available, and, of course, it would be desirable to measure all attributes in this manner.

2. Fuzzy Measurement Techniques

It is possible, however, to perform optimization operations in many situations where cardinal measurements of the second type are not available. For example, one can get as high as possible on a hill simply by being able to discern rankings--whether or not a point is higher than the point one is at. Optimization in situations involving risk can be performed with preferences measured with a uniqueness equal to that of cardinal measures of the first type. But what can be done concerning optimization when the relevant properties cannot formally guarantee measurement in any of the last three manners? How should we proceed when the representation and uniqueness theorems cannot be proved? How can we assign numbers to objects without knowing whether they represent the desired property adequately and with sufficient uniqueness that arithmetic operations can be performed with some hope of consistent, useful results?

That the task, if not scientific, is practicable is illustrated by the use of grading scales in education. Teachers grade students on a percentage scale without any proof of representation or uniqueness theorems, so that whether the grades provide a mere ranking of students, or whether they are cardinal measures of the first or second kind, or whether they are none of these is unclear. Yet addition, multiplication, and division are performed upon them, they are combined with other teachers' similar scalings (which might be compared to adding Fahrenheit and Celsius degrees given the presumed different origins and sizes of degrees in terms of ability) and aggregate grades are obtained. Despite their unscientific character, these grades are highly useful in projecting students' capabilities for advanced study, for example.

3. Fuzzy Measurement of Product Attributes and Expert Preferences

In this paper two frequently encountered measurement occasions will be considered. The first concerns the measurement of qualitative factors in the design process, which will be discussed in this section. The second involves the calculation of the relative weights that should be given the design factors (however measured) in the design phase. This implies the measurement of preferences of experts in order to choose alternative designs and the ability of such design factors to provide discriminatory information to the design team. Fuzzy techniques of measurement for these preferences will be presented in Section D.

a. Direct Scaling of Attributes With Respect to an Ideal Design

One frequently employed method of multiobjective optimization is to choose a design option by minimum compromise with some ideal but infeasible combination of design factors, $x^* = [x_1^*, x_2^*, \ldots, x_n^*]$. Suppose in the design of an aircraft one such factor was "producibility" and that 100 different designs were competing. Suppose, also, a reasonable consensus could be derived from a group of production experts, as to which of the designs was most producible and which was least producible. The ideal design in terms of producibility (x^*) is then placed at 100 on a scale line and the anti-ideal (χ) at 0, and each expert is asked either to place every design at a point on a line between 0 and 100 with calibrations at convenient points, or to provide the designs with scores between 0 and 100.

To obtain aggregate scores the scalings for each design alternative can be averged over the group of experts, with or without weights adjusting for expertise, or the median or modal score in the distribution of scores can be selected as a representative value. The final selection for the group, divided by 100 to obtain a proportion, is d_{ij}, or the *proximity index* of the jth design alternative to the ideal design with respect to the ith design factor (producibility).

Comparison of such scalings with the measurement characteristics of Section 1 reveals their scientific shortfalls. They are, however, at least based upon 0- and 100-endpoints that are associated in each decision maker's mind with actual designs. That is a favorable distinction from the educational grader's fuzzy and intuitive anchor points.

Note that the choice of zero as origin was arbitrary: there is no natural zero origin. Therefore, *at best*, the scalings could be unique up to a linear transformation, so that ratios are not meaningful. A design with a scaling of 80 cannot formally be said to be twice as producible as one with a scaling of 40.

b. Preference Scalings

Another frequent need in decision making is to scale preferences over a set of alternatives that consist of different mixes of product characteristics. For example, suppose in the aircraft design example there were five design factors in varying degrees in the 100 design alternatives, the degree of presence of each factor measured as the proximity to the ideal design in that dimension, or d_{ij}. The task is to derive utility indexes, u_j, which will permit us to formally depict the preferences among the alternatives possessed or revealed by the decision maker.

Preferences Under Risk

If decisionmakers are to make decisions under conditions of risk, where the outcomes of their choices are not wholly the result of those choices, and if *expected value* reasoning is followed by the decision maker, the measurement of the utilities must be at least unique up to a linear transformation to support the arithmetic operations necessary, given the conditions of Section 1. A method of deriving such a utility index is the von Neumann-Morgenstern methodology which involves the decision maker ranking the 100 designs initially in terms of his preferences and then comparing each intermediate design in the ranking as if received with certainty with a reference lottery whose prizes are the most- and least-preferred designs. The probability of winning the most-preferred design in the lottery option is adjusted until the subject is indifferent between it and a specific certainty option, and that probability value is chosen as a utility value for the certainty option design.

Several points are important about the method. First, it is relevant only for choices involving risk. In other circumstances the subject's attitudes to risk-bearing become entwined with his preferences among certainty options and will misrepresent his predilections. Second, the choice of 0 as the origin of the scale is arbitrary since there is no clear natural zero origin. Hence, the uniqueness of the measure in risk situations, despite appearances, is only that of a linear, not a positive multiplicative factor, transformation. Third, the derivation of such an index is frequently impracticable in terms of time and because it forces the subject to make difficult and unfamiliar choices involving fine-tuned lotteries.

Some experimentation with it for ULCE purposes may be useful, but it is doubted that it will be more than marginally useful.

Multiattribute Utility Theory (MAUT)

MAUT is a method of decomposing a total "utility" function, expressing a decision-maker's preferences over a set of components. Assume once more that there are 100 competing aircraft designs, each viewed as a mix of five design factors. Then the utility of a given design, formally measurable as a cardinal measure of the first kind, can be viewed as an additive function of the weighted utilities of the factors:

$$u(x_1,x_2,x_3,x_4,x_5) = \lambda_1 u_1(x_1) + \lambda_2 u_2(x_2) + \lambda_3 u_3(x_3) + \lambda_4 u_4(x_4) + \lambda_5 u_5(x_5) \;,$$

where x_i measures the quantities of design factor i and the λ_i's are scaling factors to assure the consistency of u(x). If the $u_i(x_i)$ are all scaled as points on the unit interval [0,1], where $u_i(x_i^*) = 1$ for x_i^* equal to the ideal value for x_i and $u_i(\chi_i) = 0$ for χ_i equal to the anti-ideal value, then $u(\chi_1, \chi_2, \chi_3, \chi_4, \chi_5)$ should equal zero. The scaling factors bring about such consistency.

The determination of the component utility functions and the scaling factors is done by interrogation of subjects comparing lottery and certainty options, even when risk is not involved. The difficulties with this procedure have been indicated above. The problem, of course, is that the only known method of achieving cardinalization of the utility functions is via the von Neumann-Morgenstern procedure which is not appropriate for nonrisky decision making. Hence, the need to experiment with fuzzy measurement methods that may yield better results.

MAUT is an expensive, time-consuming procedure that forces subjects into answering questions that are foreign to their experience. As noted above, its core methodology is ill-suited to its environment in nonrisk situations. And empirical testing of its results have indicated its poor predictability potential.

4. The Determination of Weighting Factors

The second frequently encountered need for measurement in decision making of the ULCE form is the determination of weighting factors to express the relative importance of attributes in some process. Consider again the design competition among 100 proposed designs consisting of different mixes of five design factors. Suppose again the most preferred (highest or lowest) level for each design factor is x*, and that no one design permits its attainment. It will be adopted as the (infeasible) *ideal* design.

Figure II-1 illustrates the concept for two design factors. The convex hull of the points representing candidate designs is drawn and an ideal point x* is determined (in this case) as a design that has the maximum value for each of the design factors taken over all candidates. Similarly, χ is taken as an anti-ideal point whose design factors are the minimum values taken over all candidates.

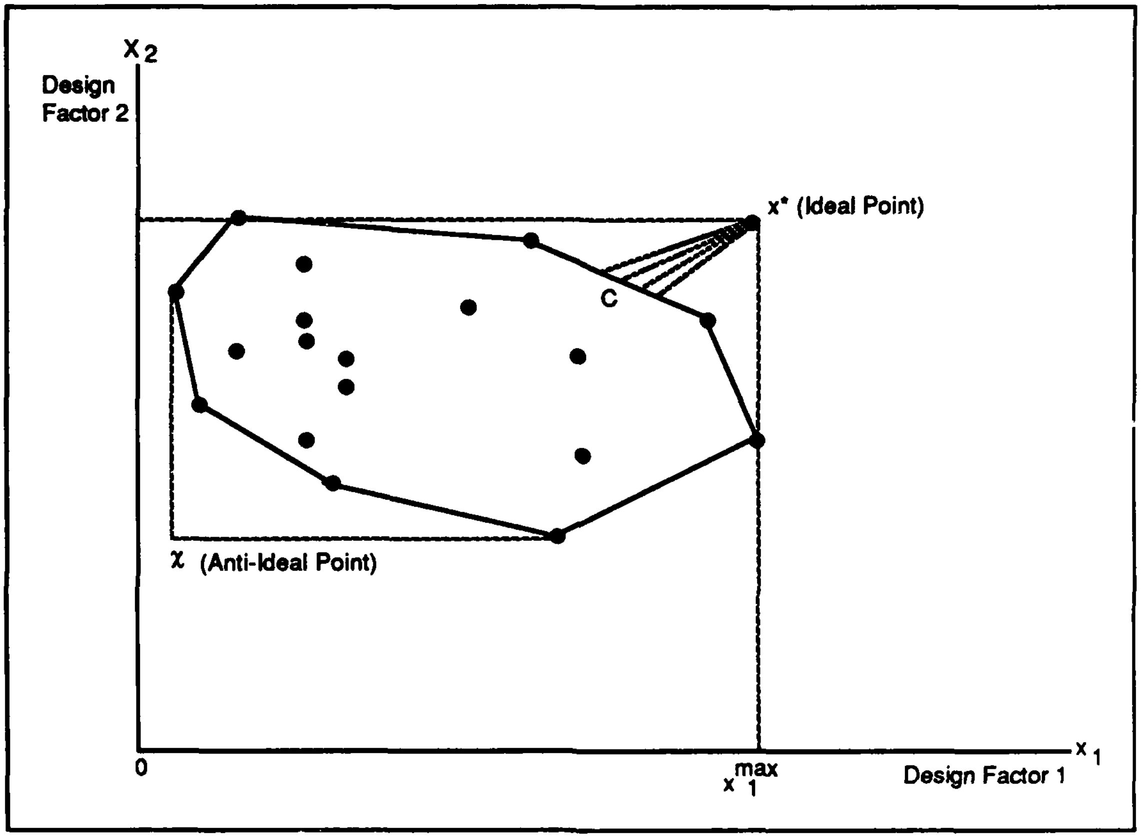


Figure II-1. Compromise Programming Optimization, With Ideal and Anti-Ideal Points, Convex Hull of Design Candidates, and Compromise Negotiation Set, C

Suppose the optimization procedure is one of compromise programming, where the design team will be presented with feasible designs that, with respect to one or more metrics, minimize the distance of feasible designs from x*. For simplicity, assume that it is desired to maximize all design factors, so that design j's ratio to the ideal design with respect to factor i is

(1) $d_{ij} = x_{ij}/x_i^*$.

Design j's factor i distance to the ideal is $(1 - d_{ij})$, and total weighted distance of design j from x* can be determined by

(2) $L_p(\lambda,j) = [\Sigma_i \lambda_i^p(1 - d_{ij})^p]^{1/p}$, $\Sigma_i \lambda_i = 1$,

where p is a positive integer and λ_i is the *information weight* given factor i in the decision process.

Compromise programming optimizes by permitting p to range over a domain of the positive integers and, by minimizing (2), isolating a set of designs and design promises that are efficient (nondominated) at minimal weighted distances from the ideal, and feasible. It may be viewed as an efficient *negotiation set* for the design team. On Figure 1, the dotted rays from x* depict the L_p's for a set of p's drawn to the upper boundary of the convex set of design candidates. The negotiation set, C, is the set of points that minimize the various L_p's in (2).

The problem at hand is the determination of the information weights λ_i. Since they are relevant to the decision process, two components of λ_i should be recognized:

The Factor or Attribute Weights, w_i. The first component is the relative weight that should be given each design factor in the search for optimal design. How important is supportability in the design as opposed to aircraft weight? The answers to this question are largely subjective and depend upon the preferences, experience, and intuition of the designer. The function of these w_i weights initially is to eliminate any attributes that are considered by the design team to be minor. After that initial use, they then must certainly enter into the λ_i as components contributing important information to the decision process.

The Discriminatory Weights, y_i. A second component of λ_i is the discriminatory power design factor i brings to the choice among design candidates or compromises among them. Weight, for example, might be an important design factor in aircraft (w_i very large), but if all candidate designs have the same weight or very similar weights, it cannot play much if any role in choosing the optimum design. The optimum design, therefore, will be determined by other factors, perhaps much less important than weight. The discriminatory weights, y_i, are designed to reduce λ_i for those factors which are similar in distance from the ideal design factor value and increase those which vary widely among designs, in recognition of the differences in discriminatory value those factors give the decision maker.

We consider briefly some fuzzy techniques for the determination of the w_i and y_i.

a. The Assessment of the Attribute Weights, w_i

Two methods of determining weights w_i are presented below, both of which rely on a decision maker's ability to make pairwise comparisons concerning the importance of attribute weights.

Cross-Factor Analysis

A matrix is formed with the attributes in both columns and rows, as depicted in Table II-1.

Table II-1. The Cross-Factor Matrix

Design Factors	1	2	3	4	5	Sum	w_i
1	–	3	0	1	2	6	0.15
2	1	–	4	3	0	8	0.20
3	4	0	–	2	4	10	0.25
4	3	1	2	–	1	7	0.18
5	2	4	0	3	–	9	0.22
						40	1.00

The subject is then asked to consider each row factor-column factor pair and to grade it in the following fashion:

4 : Factor i is much more important than factor j

3 : Factor i is more important than factor j

2 : Factor i and j are of equal importance

1 : Factor j is more important than factor i

0 : Factor j is much more important than factor i.

The diagonal, considering comparisons of a factor with itself, is left blank. Only the cells above the diagonal need be completed since cells ij and ji must sum to 4.

Row sums may then be taken and normalized as ratios to the sum of all elements. The resulting ratios may be treated as attribute weights reflecting the subjective attitudes of the subject. Various methods of aggregating the weights of all subjects may be used to get final weights.

There are some objections to the simple weight derivations used above which may be escaped by more sophisticated manners of normalizing. We need not go into them at this point. Note, however, that the method is fuzzy in that it treats ranking measurements as cardinal measures of the first type, performing strictly illegitimate operations upon them. The technique is heuristic, but does it provide weights that are consistently useful? Empirical testing alone within the ULCE context will provide answers.

Eigenvector Prioritization Method

A somewhat more sophisticated form of cross-factor technique, but which retains its fuzzy, heuristic character, is to construct the cross-factor matrix by asking the subject to determine relative weights of row and column factors, W_{ij}, which in effect are estimates of w_i/w_j. The matrix is that depicted in Table II-2.

Table II-2. The Eigenvalue Prioritization Matrix

Design Factors	1	2	3	4	5
1	W_{11}	W_{12}	W_{13}	W_{14}	W_{15}
2	W_{21}	W_{22}	W_{23}	W_{24}	W_{25}
3	W_{31}	W_{32}	W_{33}	W_{34}	W_{35}
4	W_{41}	W_{42}	W_{43}	W_{44}	W_{45}
5	W_{51}	W_{52}	W_{53}	W_{54}	W_{55}

The set of linear equations is then formed:

$$W_{11} w_1 + W_{12} w_2 + W_{13} w_3 + W_{14} w_4 + W_{15} w_5 = \phi w_1$$

$$W_{21} w_1 + W_{22} w_2 + W_{23} w_3 + W_{24} w_4 + W_{25} w_5 = \phi w_2$$

$$W_{31} w_1 + W_{32} w_2 + W_{33} w_3 + W_{34} w_4 + W_{35} w_5 = \phi w_3$$

$$W_{41} w_1 + W_{42} w_2 + W_{43} w_3 + W_{44} w_4 + W_{45} w_5 = \phi w_4$$

$$W_{51} w_1 + W_{52} w_2 + W_{53} w_3 + W_{54} w_4 + W_{55} w_5 = \phi w_5 \quad ,$$

or, in matrix form,

$$W \cdot w = \phi w.$$

It must be emphasized that the W's are specified by the subject without any explicit reference to the component w's. If the subject were perfectly consistent, so that $W_{ij} = w_i/w_j$ everywhere in the matrix, the only meaningful ϕ equals m, the number of factors. But the subject will not be perfectly consistent, and hence the system

$$[W - I\phi]w = 0$$

is solved for the m eigenvalues ϕ that are consistent with the system. The maximum (or Forbenius) root ϕ^* will be (since W is positive and nondecomposable) real, positive, and unique, and extracts the greatest consistency possible from the answers. The eigenvector w^*, which is determined by ϕ^* normalized to sum to 1, will be positive (since W is positive and nondecomposable) is chosen as the set of attribute weights to be used in the decison making.

Note the technique is fuzzy because it treats the W_{ij} as cardinal measures of the second type without proof. The subject determines them not as ratios but as rough scalars, and they merely reflect rankings. In any event, for ratios to be meaningful in the formal sense of Section 1, a natural zero must be definable, and this is not a clear concept in the subject's decisions.

5. Estimation of the Discriminatory Weights

a. Entropy Measures of the Discriminatory Weights

One method of obtaining the weights y_i, which yield information concerning the discriminatory power of the attributes, is to adapt the entropy model for estimating the expected information obtained from observations. Space does not permit development of entropy theory in an information context, but it is a widely used model available in decision theory textbooks.

As noted above, the more variability in the distances to the ideal attribute value that candidate designs possess, the greater the *contrast intensity* of that attribute, and the more decision information it transmits to the decision process. Entropy measures are designed to yield indexes of this information.

Define, from (1),

(3) $D_i = \Sigma_j d_{ij}$,

or the sum of the proximity ratios for a given design factor over the 100 design candidates. Then, the entropy measure of the discriminatory power of the ith design factor is defined as

(4) $$e(d_i) = -K \Sigma_j (\frac{d_{ij}}{D_i} \ln(d_{ij} / D_i)) , \quad K > 0,$$

where K is a parameter to be determined. Now, the maximum value for $e(d_i)$ is attained when all d_{ij} are equal for all designs of the m design candidates, or

$$e(d_i)_{max} = -K(m/m)\ln(1/m) = K \ln (m).$$

By setting $K = 1/\ln m$, this maximum value is set to 1, and the normalized entropy measure of the ith design factor becomes

(5) $$e(d_i) = -(1/\ln m) \Sigma_j(d_{ij}/D_i) \ln(d_{ij}/D_i) ,$$

so that $0 \leq 1$. The zero lower limit is approached as the d_i approach the anti-ideal values. Finally, the total entropy over all attributes or factors i is defined as

(6) $$E = \Sigma_i e(d_i) .$$

Now, the greater the similarity in the proximity ratios for a given attribute, the closer $e(d_i)$ is to 1, and the smaller the information transmitted by it. When $e(d_i) = 1$, no information at all is given the decision maker that permits him to use factor i as a discriminating attribute. Because the weights y_i are taken as rising with greater discriminatory power, we will work in its definition with $(1 - e(d_i))$. We may then normalize the y_i so that $\Sigma_i y_i = 1$ by defining

(7) $$y_i = \frac{(1 - e(d_i))}{n - E} ,$$

since $\Sigma_i (1 - e(d_i)) = n - E$.

An example may help to clarify the method and illustrate its usefulness. Suppose three design factors and four design candidates exist. The measures for the design factors (exact or fuzzy) are given in Table II-3. The ideal design is taken as the maximum value in each attribute column. Table II-4 lists the proximity ratios (1), or $d_{ij} = x_{ij}/x_i^*$.

Table II-3. Design Factor Scores for n = 3 Factors and m = 4 Designs

Design (j)/Factor (i)	1	2	3
1	7	100	4
2	8	60	4
3	8.5	20	6
4	9	80	2
Ideal	9	100	6

Table II-4. Proximity Ratios

Design (j)/Factor (i)	1	2	3
1	0.778	1.0	0.667
2	0.889	0.6	0.667
3	0.944	0.2	1.000
4	1.000	0.8	0.334
$D_i = \Sigma_j\ d_j$	3.611	2.6	2.668

Then

$$1/e(d_i)_{max} = 1/\ln 4 = 1/1.1386 = 0.721$$

and

$$\begin{aligned}
e(d_1) &= -0.721[(0.215)(-1.535) + (0.246)(-1.402) + (0.261)(-1.342) + (0.277)(-1.284)] \\
&= 0.721[1.381] = 0.996 \\
e(d_2) &= -0.721[(0.385)(-0.956) + (0.231)(-1.466) + (0.077)(-2.565) + (0.308)(-1.179)] \\
&= 0.721[1.267] = 0.914 \\
e(d_3) &= -0.721[(0.250)(-1.386) + (0.250)(-1.386) + (0.375)(-0.981) + (0.125)(-2.078)] \\
&= 0.721[1.321] = 0.952.
\end{aligned}$$

Therefore,

$$E = \Sigma_i\ e(d_i) = 2.862,$$

and

$y_1 = 7.246(0.004) = 0.029$

$y_2 = 7.246(0.086) = 0.623$

$y_3 = 7.246(0.048) = 0.348$.

Thus, design factor 1 yields little discriminatory power in the choice process because, as is seen in Table II-3, its d_{1j} values are very close together. Factor 2 is most powerful in yielding such information, and factor 3 is about half as useful as factor 2.

Finally, the question arises on the manner of combining w_i and y_i into the λ_i or the information weights necessary for the calculation of $L_p(\lambda,p)$ in (2). A simple manner of performing this is to define

$$\text{(8)} \qquad \lambda_i = \frac{w_i \bullet y_i}{\sum_i w_i \bullet y_i} \ .$$

Suppose the attribute weights were determined by one of the methods discussed above to be

$w_1 = 0.8$

$w_2 = 0.1$

$w_3 = 0.1$.

Hence,

$\lambda_1 = 0.023/0.120 = 0.192$

$\lambda_2 = 0.062/0.120 = 0.516$

$\lambda_3 = 0.035/0.120 = 0.292$.

Because of its high attribute weight, factor 1 is saved from the consequences of its negligible discriminatory weight, but its total weight is much reduced from what w_1 alone would have given it. Also, the great discriminatory weights given factors 2 and 3 lift them substantially above their attribute weights in the information weights λ_i.

6. Conclusion

This paper attempts within a brief compass to depict the severe restriction that the strict mathematical theory of measurement places upon the quantification of important attributes in a design process. It urges the desirability of research into the feasibility and usefulness of heuristic or fuzzy methods of quantification which may prove to be useful in ULCE design optimization. Finally, some of the techniques of fuzzy measurement currently available have been presented, in brief form as illustrations of their potential. Research into such methods with direct applicability to ULCE decision processes, including the testing of the methodologies within these processes, is recommended.

B. MULTIOBJECTIVE OPTIMIZATION AS A SUPPORT TO ULCE

This brief paper is meant to provide a nontechnical introduction to a few of the available multiobjective optimization techniques that are relevant to Unified Life Cycle Engineering (ULCE). They will be illustrated by a simple prototypical example of aircraft design that has been constructed for pedagogical purposes. As an economist, the author herewith files a disclaimer concerning the airworthiness of any aircraft design that emerges from these simple models. He certainly would not accept an invitation to fly in them! The hope, of course, is that the techniques are applicable to the extremely complicated realistic design process.

1. Optimization Modeling: Concepts and Terms

Structuring a decision process in a modeling framework involves the designation of four of its components--objectives, constraints, goals, and division variables.

a. Objectives

The objectives are the unbounded and directionally specified (maximize or minimize) requirements of the process.

b. Constraints

A constraint is a fixed requirement of the process that cannot be violated. Taken together as a set, they divide all possible solutions into two groups--those that are *feasible* in their conformity to the constraint requirements and form the *feasible region* and those that are *infeasible*. The constraints express limitations imposed upon the decision process by physical, economic, preference, or other forces. Expressed as functions, their left-hand sides depict the relation of the decision variables to the particular restrictive factor, and the right-hand side--termed the *restraint* of the constraint--is the floor or ceiling value of that restriction.

c. Goals

A constraint becomes a goal that the restriction it expresses is to be met as closely as possible. A goal is an optimized constraint. For example, a restriction on the amount of labor to be employed by a firm to no more than n persons is a constraint that can be satisfied by any value less than n. If the requirement is that it be satisfied as closely as possible to the ceiling n, the restriction becomes a goal.

d. Decision Variables

The objective, constraint, and goal functions relate the decision variables or attributes to the requirements of the process directly and, hence, indirectly determine the interdependence of these variables and attributes to each other. Those variables' and attributes' values are determined by the requirements of the model, and those values determine the *solution* or state of the system. An *optimal* solution is a set of values that conforms to all of the requirements of the model.

2. A Hypothetical Case: Aircraft Design

Suppose a design process is undertaken to configure a new attack aircraft. Five performance characteristics are of major concern:

1. Life cycle cost
2. Takeoff roll
3. Maximum speed
4. Range
5. Payload.

Four design factors contribute to these performance characteristics:

1. Wing area
2. Engine thrust
3. Radar range
4. Landing gear strength

Restrictions upon the freedom of the designers to combine these factors are of several types.

- Logistics considerations must limit the fuel consumption which is related to weight of the aircraft.

- Engineering factors relate engine thrust and landing gear strength, restricting their ability to be determined independently.
- Engineering factors also relate wing area and landing gear strength.
- Manufacturing limitations restrict radar range to a ceiling value.

Suppose the interrelationships of the decision variables--wing area (x_1), engine thrust (x_2), range range (x_3), and landing gear strength (x_4)--are related linearly to the performance characteristics as listed below.

1. Cost: $C = \sum_i c_{1i} x_i$, $i = 1, 2, 3, 4$
2. Takeoff roll: $T = \sum_i c_{2i} x_i$
3. Maximum speed: $S = \sum_i c_{3i} x_i$
4. Range: $R = \sum_i c_{4i} x_i$
5. Payload: $P = \sum_i c_{5i} x_i$

Further, assume the decision variables relate to the constraints as follows.

1. Weight restriction: $\sum_i a_{1i} x_i \leq b_1$
2. Engine thrust/landing gear restriction: $x_4 - a_{22} x_2 \geq 0$ where a_{22} is the increment in landing gear strength required per unit of engine thrust
3. Wing area/landing gear restriction: $x_4 - a_{31} x_1 \geq 0$
4. Radar range restriction: $x_3 \leq b_2$

Finally, all decision variables must be nonnegative:

$x_1, x_2, x_3, x_4 \geq 0$.

What types of optimization models are available to help the designer in achieving a *good* design? Despite the use of the term "optimization", no modeler would suggest that these techniques would produce an aircraft that was definably "the best possible alternative in the face of the given restrictions." That judgment must be based upon the knowledge, intuition, and experience of the designers, and those qualities can never be encapsulated in the rigid and oversimplified relations illustrated above. The purpose of the model is to aid the designers in their search for good design and, ideally, to suggest aspects of the design that may have been overlooked in the absence of the model.

Three basic approaches with variations to providing such insights are illustrated below.

3. Objectives-As-Constraints Approach

One straightforward manner of obtaining solutions is to select one objective as primary to be used as the objective function to be optimized and to convert the other objectives to constraints. For example, suppose cost is chosen in the design example as primary constraint, and the desire is to minimize it. The other four objectives are made into constraints by imposing restraints that must be met, those restraints being derived from independent research. For example:

- Takeoff roll must not exceed K_2 feet;
- Maximum speed must be at least K_3 knots;
- Range must be at least K_4 kilometers;
- Payload must be at least K_5 tons.

The model can then be formalized as follows:

(1) 1. Minimize $C = C_{11} x_1 + c_{12} x_2 + c_{13} x_3 + c_{14} x_4$

Subject to:

2. $c_{21} x_1 + c_{22} x_2 + c_{23} x_3 + c_{24} x_4 \leq K_2$
3. $c_{31} x_1 + c_{32} x_2 + c_{33} x_3 + c_{34} x_4 \geq K_3$
4. $c_{41} x_1 + c_{42} x_2 + c_{43} x_3 + c_{44} x_4 \geq K_4$
5. $c_{51} x_1 + c_{52} x_2 + c_{53} x_3 + c_{54} x_4 \geq K_5$
6. $a_{11} x_1 + a_{12} x_2 + a_{13} x_3 + a_{14} x_4 \leq b_1$
7. $- a_{22} x_2 + x_4 \geq 0$
8. $- a_{33} x_3 + x_4 \geq 0$
9. $x_3 \leq b_2$
10. $x_1, x_2, x_3, x_4 \geq 0.$

Several characteristics of this model are noteworthy. Most important, it permits a cost-benefit approach to optimal design without the need to reduce the five objectives to a single function for optimization. Each objective is calibrated in its own natural units and retains its identity. This escapes the frequently voiced objection that faced with multiple objectives an optimization model must choose only one of them for consideration or else formulate a single objective function calibrated in some homogeneous unit into which dollars, feet, knots, kilometers, and tons are converted.

Secondly, the relations in (1) need not be linear. Solution algorithms exist for nonlinear objective and/or constraint functions, although restrictions upon the functions, which are sufficient to guarantee global constrained extrema rather than merely local extrema, are not trivial. Nonetheless, even when only local solutions are forthcoming, repeated solutions of the model obtained by starting the algorithms at widely separated initial points yield information about good design compromises or even a basis for confidence that a recurring solution is indeed a global optimum.

It follows from the statement of the purposes of modeling in Section 2 that the goal of the modeler cannot be to present "the answer" to the design team Rather, suggestive insights to its collective wisdom are the desiderata. These are obtained by *parametric displacement* or *sensitivity analysis* which permits the design team to change the a, b, c, or K parameters to observe the manner in which the solutions are altered. If the current solution yields K_4 tons of payload, what would happen to cost C if the payload requirement were reduced to $K_4 - \Delta K_4$? Would maximum speed rise? If minimum takeoff roll were relaxed to $K_1 + \Delta K_1$, how would range and payload change? These displacements yield four types of information to the modeler and the design team.

1. They reveal how "robust" the optimal solutions are to parameter values. For example, if the same combination of $[x_1, x_2, x_3, x_4]$ is optimal for wide variations in the cost coefficients c_{11}, c_{12}, c_{13}, and c_{14}, the design team can have some confidence in the underlying stability of the recommended design.

2. They offer a means of dealing with uncertainty about the exact values of important parameters. By bracketing important parameters with lower and upper bounds, and solving the model, the design team can get insights into the practical significance of uncertainty about the exact values of such parameters.

3. Such bracketing permits decisions about where research for greater precision of parameters should be concentrated. If, when a parameter value is reduced by 25 percent from its given value and increased by 25 percent, solutions do not differ significantly, it makes little sense to spend a large amount of time trying to get better estimates of it. On the other hand, if ±10 percent displacements of a parameter lead to large solution changes, greater research into the parameter estimate is probably cost effective.

4. Only by such displacement is it possible to discover what parameters are driving the model. Large models speedily exhaust one's intuitive understanding of its interdependence and tend to become black boxes. If, for large changes in important parameters, the only two restraints that bind the

solutions are K_2 and K_3, it then can be concluded that the minimum requirements for maximum speed and range are ultimately determining the suggested designs of the aircraft.

Finally, the positions of primary and secondary objectives can be interchanged to determine new sets of solutions. For example, the primary objective can be to maximize payload, with cost taking its position as a secondary objective that cannot exceed K_1 dollars. A different set of solutions and trade-offs can then be obtained with parameter displacements for comparison with solutions obtained with cost as primary objective.

4. Goal Programming

An alternative approach to the optimization is to convert all of the objectives to goal-type requirements. The model can then be written:

(2) 1. Minimize $Z = w_1^+ d_1^+ + w_2^- d_2^- + w_3^- d_3^- + w_4^- d_4^- + w_5^- d_5^-$

Subject to:

2. $c_{11} x_1 c_{12} x_2 + c_{13} x_3 + c_{14} x_4 - d_1^+ + d_1^- = K_1$

3. $c_{21} x_1 c_{22} x_2 + c_{23} x_3 + c_{24} x_4 - d_2^+ + d_2^- = K_2$

4. $c_{31} x_1 c_{32} x_2 + c_{33} x_3 + c_{34} x_4 - d_3^+ + d_3^- = K_3$

5. $c_{41} x_1 c_{42} x_2 + c_{43} x_3 + c_{44} x_4 - d_4^+ + d_4^- = K_4$

6. $c_{51} x_1 c_{52} x_2 + c_{53} x_3 + c_{54} x_4 - d_5^+ + d_5^- = K_5$

7. $a_{11} x_1 a_{12} x_2 + a_{13} x_3 + a_{14} x_4 \leq b_1$

8. $a_{22} x_2 + x_4 \geq 0$

9. $- a_{31} x_3 + x_4 \geq 0$

10. $x_3 \leq b_2$

11. $x_1, d_i^+, d_i^- \geq 0, \quad i = 1, 2, 3, 4.$

The d_i^+ are the amounts by which the left-hand sides of the goal constraints (2.2-2.6) exceed the restraints K_i, and the d_i^- are the amounts by which the K_i are under-achieved. The w_i^+ and w_i^- are the weights placed upon over- or underachievement of the goals. For example, (2.2) is the cost objective. No penalty is placed upon underachieving K_1, so $w_1^- = 0$ and d_i^- does not appear in the objective function. But, exceeding the budget restraint K_1 is penalized, so d_1^+ is among the discrepancies to be minimized after receiving its weight w_1^+. On the other hand, all of the other goals strive to meet or exceed a floor value, K_i, and hence underachievement (d_i^-) is to be minimized after weighting. All of the goals, therefore, are one-sided: either over- or underachievement is penalized. If it is desired to penalize departures in both directions, then both weighted terms must enter the objective function (e.g., $(w_1^+ d_1^+ + w_1^- d_1^-)$).

Note that the constraints (2.7-2.10) remain as written in system (1). The extent of their under- or overachievement, as long as the restraints are not violated, is not a matter of concern. They may be written with d_i^+ and d_i^- terms if desired, but they do not enter the objective function with nonzero weights. Hence, a constraint may be viewed as a goal whose slack or surplus variables do not appear in the objective function.

One of the additional complexities that goal programming introduces is that a set of weights w_i^+ and w_i^- must be devised. Moreover, they must be measured, at least formally in manners that yield a cardinal measure of merit (i.e., unique up to a linear or affine transformation). The problems of deriving such weights are discussed in an accompanying paper.

In a linear model, for every goal function either d_i^+ or d_i^- (or both) will be driven to zero by the optimization. Nonlinear models will not necessarily do this and may create problems in this respect.

The goal programming model presents the same opportunities for parametric ranging that were discussed in Section 3. They need not be repeated.

5. Multiobjective Linear Programming

An approach to optimization which is less ambitious in its aims than the methods of Sections 3 and 4 is multiobjective linear programming. Its purpose is to optimize in a weak sense by seeking out all of the nondominated solutions in the feasible region determined by the constraints.

In multiobjective linear programming all of the objectives are retained as objective functions. To illustrate in a two-dimensional space for purposes of geometric presentation, suppose the design problem were the following:

Maximize $Z_1 = x_1 + x_2$

Maximize $Z_2 = x_2$

Subject to:

$$x_1 + 6x_2 \leq 108$$

$$x_1 + 2x_2 \leq 40$$

$$x_1 + x_2 \leq 24$$

$$3x_1 + x_2 \leq 42$$

$$4x_1 + x_2 \leq 52$$

$$x_2 \leq 17.5$$

$$x_1, x_2 \geq 0 \;.$$

The six primary constraints, along with the two nonnegativity constraints, define the feasible region F in Figure II-2. That region comprises all combinations of the decision variables $[x_1, x_2]$ that conform to *all* of the constraints. The linear segments or edges on the upper boundary of the *polytope* are portions of the six primary constraints, and their intersections form the vertices or extreme points of the polytope. The lower bounds are the axes of the diagram, enforcing the nonnegativity constraints.

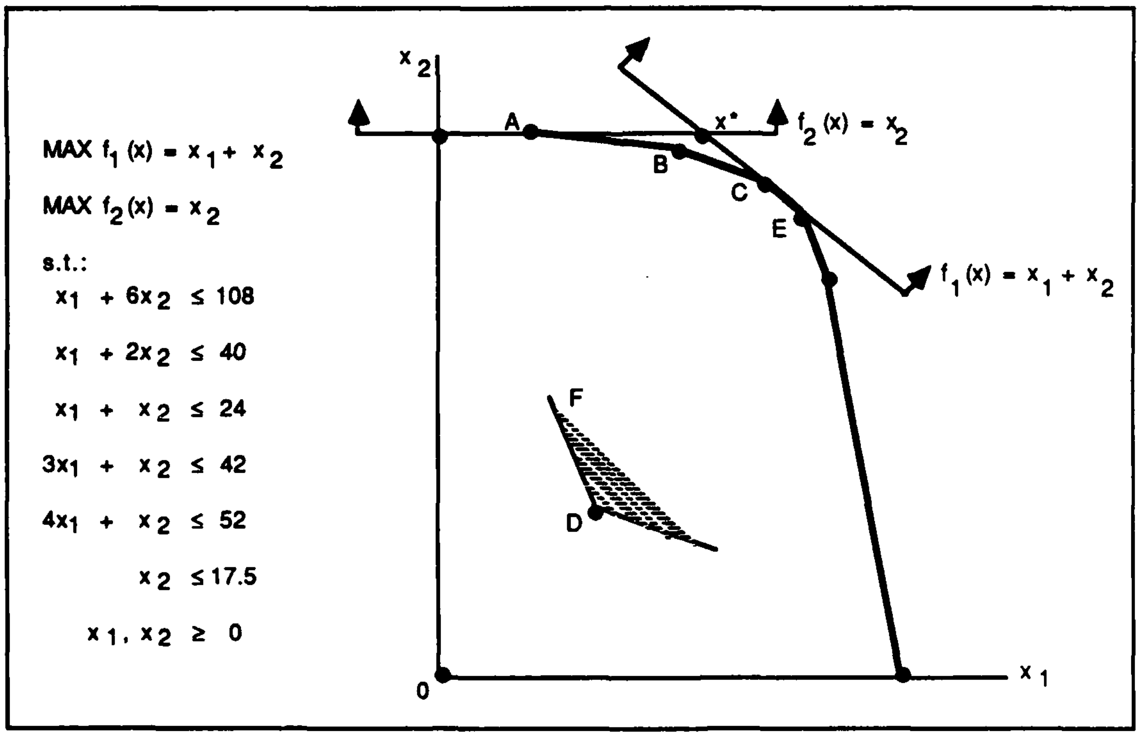


Figure II-2. The Concepts of Dominant and Non-Dominant Solutions

The contour lines of the two objective functions drawn in Figure II-1 are the contours that would be optimal if only the relevant objective function were to be considered. Thus, because the contour line for $Z_1 = f_1(x)$, which is optimal, coincides with an edge of the polytope CE, any point on that edge is an optimal solution considering Z_1 only, because that set of points lies as far from the origin as Z_1 can attain without leaving F. Similarly, vertex A is the optimal solution if only $Z_2 = f_2(x)$ is considered.

However, *both* objective functions are relevant, so the optimal solutions must be defined as those solutions (points within F) from which movement that increases the value of one of the objective functions can only be made by reducing the value of the other. That is, the optimal solutions are nondominated--no other solution can yield a higher value for one of the objective functions and at least as high a value for the other.

On Figure II-1, consider point D in the interior of F. The angle drawn is formed from the contour lines of Z_1 and Z_2 that go through D. Any move from D within the area subtended by that angle will result in a greater value for one of the objectives and at least as much of the other. Hence, D is a *dominated* solution and cannot be optimal in the stated sense.

Application of this criterion of nondominance in Figure II-2 reveals that only the piecewise-linear portion of the boundary formed by ABC contains nondominated points. In terms of the present context, designers should concentrate upon combinations $X = [x_1, x_2]$ of factors on this set. Note, interestingly, that even though the edge CE is optimal for Z_1 taken singly, only its end point C is now optimal in the sense of nondominance. By moving up from E along the edge CE, the value Z_1 remains the same, but as higher contour lines of $f_2(x)$ (not drawn) are attained, Z_2 rises. At C that possibility ends.

With this two-dimensional introduction it is now possible to construct model 3 for the example at hand:

(3) 1. Minimize $C = c_{11} x_1 + c_{12} x_2 + c_{13} x_3 + c_{14} x_4$

2. Maximize $T = c_{21} x_1 + c_{22} x_2 + c_{23} x_3 + c_{24} x_4$

3. Maximize $S = c_{31} x_1 + c_{32} x_2 + c_{33} x_3 + c_{34} x_4$

4. Maximize $R = c_{41} x_1 + c_{42} x_2 + c_{43} x_3 + c_{44} x_4$

5. Maximize $P = c_{51} x_1 + c_{52} x_2 + c_{53} x_3 + c_{54} x_4$

Subject to:

6. $a_{11} x_1 + a_{12} x_2 + a_{13} x_3 + a_{14} x_4 \leq b_1$

7. $- a_{22} x_2 + a_{14} x_4 \geq 0$

8. $- a_{33} x_3 + x_4 \geq 0$

9. $x_3 \leq b_2$

10. $x_i \geq 0, \quad i = 1, 2, 3, 4$.

A modified version of the ordinary single objective simplex algorithm for solving linear programming problems exists--the Multicriterion Simplex Method--to solve for all of the nondominated solutions on the feasible region polytope defined by (3.6-3.10). No such solution technique exists for nonlinear programming formulations.

The advantage of the multiobjective linear programming approach is that it does not require any weighting of objectives or determination of restraints for objective functions, as the prior two approaches did. Its disadvantage, of course, is that it yields nonunique solutions. However, this may be an advantage in that it gives a design team a set of *good* design choices with which to negotiate, plus the assurance that no other design could obtain more of one or more performance characteristics without sacrificing some of at least one other characteristic.

An important variant of this technique is *compromise programming*. It consists of defining an *ideal point* X* in the factor space, with the individual factors $[x_1^*, x_2^*]$. The ideal point is a nonfeasible collection of factors that would be in some sense the most desirable design if constraints did not exist. For example, on Figure 1 X* is defined as the intersection of the two optimal contour lines for Z_1 and Z_2. Compromise programming consists of discerning a *compromise set* of feasible solutions by minimizing a set of distance metrics from X* to the feasible region within the nondominated solution set.

A useful complementary technique to multiobjective linear programming that is accomplished easily as a byproduct of the multicriterion simplex method is *multiparametric decomposition*. If instead of maximizing the five objective functions of (3), the weighted sum

(4) $\quad Z = \lambda_1 C + \lambda_2 T + \lambda_3 S + \lambda_4 R + \lambda_5 P$

is formed, where $\sum_i \lambda_i = 1$, all of the nondominated solutions can be traced out by permitting the λ_i's to take all permissible values. Note these weights are not measures of merit: they are simply analytical constructs. In terms of Figure 1, by forming

$$(5) \qquad Z = \lambda_1 f_1(x) + (1 - \lambda_1) f_2(x) \ ,$$

and letting λ_1 vary from 0 to 1, nondominated solutions on ABC can be obtained.

More importantly, the ranges of the λ_1 for which a given point (or points) is optimal can be determined, hopefully giving the design team some insights into the domains of relative importance assigned for which a given design would be "best." The problem has been decomposed in a multiparametric manner, and these ranges of the λ_i can be derived expeditiously from the multicriterion simplex algorithms.

6. Conclusion

This brief and nontechnical presentation contains three types of multiobjective optimization techniques that have immediate relevance to ULCE. Several complications have been treated cavalierly in order to emphasize the essential features of the methodology. The measurement of figures of merit with sufficient uniqueness to permit the necessary arithmetic operations will be treated in a separate paper. And the complications of non-linearity, especially when they yield "nonconvex" problems for solution, should be treated at greater length than was possible in this brief paper.

C. PROPAGATION OF DESIGN CHANGES AND INFORMATION (CONFIGURATION AND CHANGE CONTROL PROBLEMS)

Configuration management must be an integral part of Unified Life Cycle Engineering (ULCE) development. Configuration management provides a foundation for rigorous design management discipline in the performance of ULCE tasks.

The implementation of configuration management within the ULCE system must extend throughout the design chain between each successive task, each contractor, and each subcontractor. Configuration management relates design objectives and design planning (configuration identification) to program and project management authority in the ULCE process.

ULCE benefits from configuration management through continuous, formal status accounting and change control over the life cycle of the design. The system implementation for Unified Life Cycle Engineering must address four areas of adequacy criteria for configuration management.

1. The ULCE system must provide for adequate planning of the hardware and computer software management, technical tasks, and organization (including budgeting and staffing) necessary to meet configuration management objectives.
   - The system must provide for a documented planned approach for management of configuration management efforts.
   - The system must provide for coordination with other activities to assure compatibility of hardware and computer software configuration management objectives, techniques, data formats, schedules, and procedures.
   - The system must assure that management determines hardware and computer software configuration management activities are proceeding as planned and for taking appropriate management action.
2. The ULCE system must provide for configuration identification and auditing of hardware and computer software, physical, and functional characteristics.
   - The system must provide for defining and implementing the required contractor's and subcontractor's engineering management tasks necessary to support formal functional and physical configuration audits.
   - The system must provide for defining authorities, responsibilities, and procedures to effect an engineering release system for hardware and computer software.
   - The system must assure the engineering adequacy, currentness, and completeness of contractor's and subcontractor's engineering drawings, specifications, and computer software documentation.
   - The system must assure the engineering documentation adequacy, currentness, and completeness of the computer software aspects of firmware.
3. The ULCE system must provide for controlling changes, deviations, and waivers to the established hardware and computer software configuration identification.
   - The system must provide for justification of a contractor/subcontractor-initiated change and a determination of the classification of the change.
   - The system must provide for describing the flow process for contractor/subcontractor-initiated changes, deviations, and waivers from origination to implementation.
   - The system must require any changes made to be processed through the contractor's configuration change board.
   - The system must describe the functions and membership of the contractor's configuration change board.
   - The system must require all proposed changes, including subcontractor changes, be reviewed by specialties such as reliability, maintainability, system safety, quality control, manufacturing, etc.

- The system must define how the contractor/subcontractor assures the requirements for the hardware and software effectivity points of change are met.
- The system must limit to a reasonable amount the number of engineering orders attached to drawings before they are incorporated by a revision to the drawing.
- The system must require adequate contractor internal configuration control of nondeliverable software (including computer-aided design and computer-aided test), which is used to support the design/test of deliverable hardware and software.

4. The ULCE system must provide for recording information needed to manage the hardware and computer software configuration effectively.
   - The system must provide for developing and maintaining records relative to hardware and computer software, which list the approved configuration identification; determine and provide review of cost, schedule, and technical impacts of proposed changes; show the status of proposed changes to the configuration; and show implementation status of approved changes.
   - The system must provide a method of controlling changes to design prior to official acceptance of the design.
   - The system must provide for program configuration index(es) which include version description documents or the equivalent.
   - The system must provide for an adequate library system for both deliverable and nondeliverable software (including computer-aided design and computer-aided test) within the configuration management system.

D. THEORY OF MEASUREMENT (HOW TO QUANTIFY *ILITIES*)

A simple definition of an ULCE system is one that provides decision support to a designer such that he/she can consider a number of *ilities* such as performance, cost, producibility, reliability, maintainability, etc., in his/her design.

A non-trivial problem, however, is that of classifying a given design into categories such as reliable and unreliable, etc. First, there must be an acceptable and quantifiable definition of the *ility*. Next, one must have a means of utilizing such definitions in classifying given designs.

The field of Pattern Recognition is an unsolicited area that might be of great help in solving some of the above problems. A common definition of a "classifier" is a device that sorts data into categories or classes. In other words a classifier can make decisions regarding membership of a particular sample data to a category or class. The classifier makes this decision by properly evaluating certain parameters or features of the given sample data. In the simplest case, a classifier classifies a given sample data (a design) into one of two categories.

For example, one classification task could be that of classifying a digital circuit design into one of two categories--reliable or not reliable. Given the above design (i.e., sample data), the classifier might consider such features as number of ICs, number of layers used in the production of that design, thermal characteristics of all components, etc., to come up with a decision as to whether the given design is reliable or not. In order to make such a decision, the classifier compares the features of the sample design to those of a "verified" model of reliable designs, with the model already existing in the classifier data base. The process of developing and inputting a verified model into a classifier is known as "classifier training."

A question that might arise here is how does one verify the training samples to start with? The answer to this question is that for each *ility* there are always threshold values that have been established throughout the years. Some of these threshold values have scientific foundations and some are simply results of expert opinion in that particular field. For example, in any factory, independent of the type of product (i.e., digital circuits, turbine engine parts, etc.), there is an acceptable level for producibility. Most often, the product yield is used as a measure of producibility, e.g., any part with a yield of 60 percent might be labeled as not producible.

The main question to be asked, however, once a Part (design) has been labeled not producible, is how should the design be modified in order for the product to be producible? Which features of the design did cause the low yield? Are those features and characteristics of the design responsible for the low yield even measured and checked as part of the design process? Does the number of design changes that a particular design has gone through have anything to do with unproducibility of that design? Is the work shift during which the part was built or assembled in any way related to the low yield?

In the field of Pattern Recognition, the problem described above is known as Feature Selection, i.e., given a set of features (design parameters) that describe a class of samples (producible designs), find those features (if any) that are critical and have the most discriminating power for classifying new samples (new designs).

The majority of feature selection methods primarily deal with two class problems. However, most of these techniques can be extended to address multiclass applications.

Furthermore, there are a number of feature selection and pattern recognition techniques that are specifically developed for multiclass problems.

E. DECOMPOSITION OF THE DESIGN PROCESS

1. Introduction

The design process in an ULCE environment will be based on a system engineering (SE) approach. The current state of the art in SE is documented in the *System Engineering Management Guide* (SEMG). The system hierarchy and functional decompositions are integral parts of the SE approach [Ref. 17].

A structured approach is needed to apply the SE process to advanced concepts and design innovations. Multilevel Optimization using Linear Decomposition (MOLD) is a software tool that provides a step toward such a structured approach.

The MOLD software offers significant advantages when applied to the SE process. MOLD provides designers and system engineers with tools to decompose the requirements flowdown and allocation process into design tasks (the design process decomposition) for complex design concepts requiring total integration of engineering specialties. MOLD is highly compatible with the use of design optimization to resolve conflicts within system elements, although MOLD can also be used with other design solution techniques.

MOLD is based on an object-centered representation of the design process. MOLD structures the design process decomposition based on interconnections among user-defined design relationships. The design relationships are represented as objects using the Symbolics Flavor System.

2. How MOLD Works

MOLD analyzes the connectivity of the design process to identify levels of the system hierarchy and system elements that are decoupled from one another (Figure II-3). At this stage, candidate design tasks are identified. The user can browse through these design tasks (or optimization subproblems) to inspect design relationships included in each task and the interfaces between tasks. MOLD is able to restructure a design process containing 470 design relationships in about 30 seconds of the user's time. This makes it reasonable for the user to examine the impact of changing the design concept (and thus the design relationships) or the top level goals and requirements. MOLD also allows the user to modify the design process decomposition by moving design relationships from one

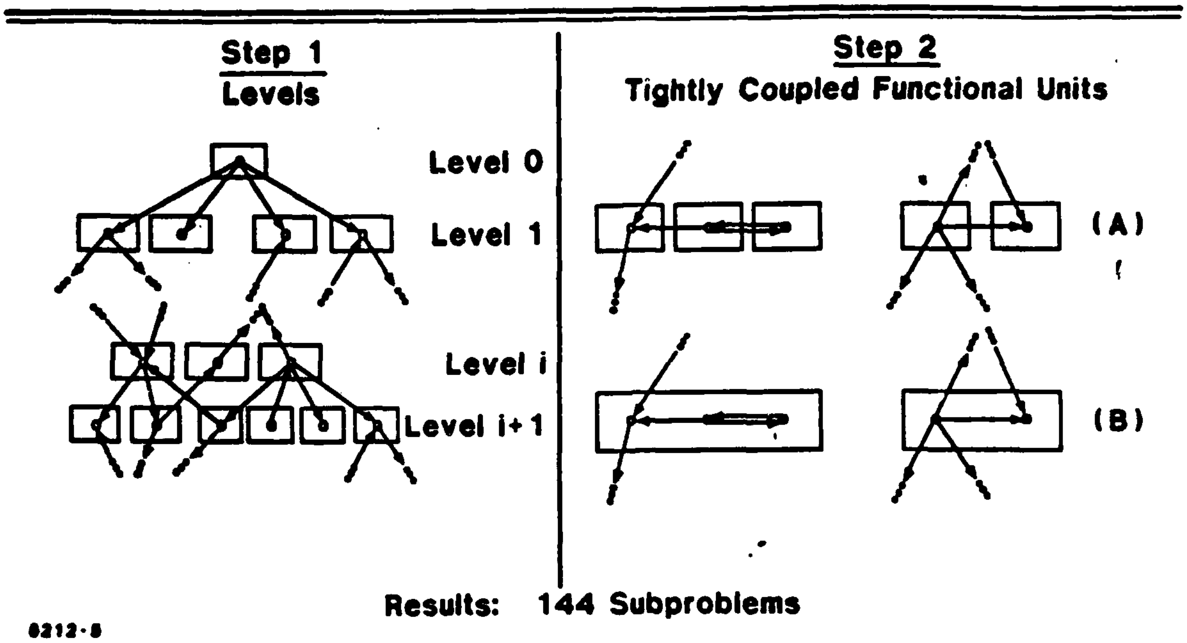


Figure II-3. Decomposition Technique

design task to another. MOLD automatically recomputes the design process decomposition structure required to accommodate these changes.

The requirements allocation and flowdown involves quantitative examination of the design relationships (rather than just considering the connections between them). In the classical SE/design process, bounds are placed on the parameters that are passed between design tasks to effectively decouple them.

MOLD provides an optimization-based approach that overcomes many of the problems encountered in using the classical approach. It may be very difficult to identify bounds on the parameters that allow the designer enough flexibility to resolve conflicts within each design task. Another problem is that the number of alternative ways to decouple the design efforts grows exponentially with the complexity of the design process. Finally, the design process decomposition is not static. It is often advantageous to restructure parts of it as the design process is iterated and different requirements turn out to be critical.

3. Solution Strategy

The MOLD solution procedure is based on the technique, *Linear Decomposition,* developed by Dr. Jaroslaw Sobieski and his colleagues at the NASA Langley Research Center [Ref. 20]. The technique prescribes a strategy for iterating between design tasks by setting and passing parameter values. Convergence is achieved in a design process with a hierarchical structure by quantifying the effect of changing the value of a parameter and returning this information to the design task where the value of the parameter is set.

The initial structure identified by MOLD is rarely hierarchical. In fact, most design problems have a more complex structure in which the system elements have more than one *parent* (Figure II-4). This complex structure can result in divergence of the overall design process. This divergence can be avoided through careful formulation of the subproblem interfaces. At Lockheed-Georgia, development work is currently focusing on a technique that uses equality constraints to assure convergence for nonhierarchical systems.

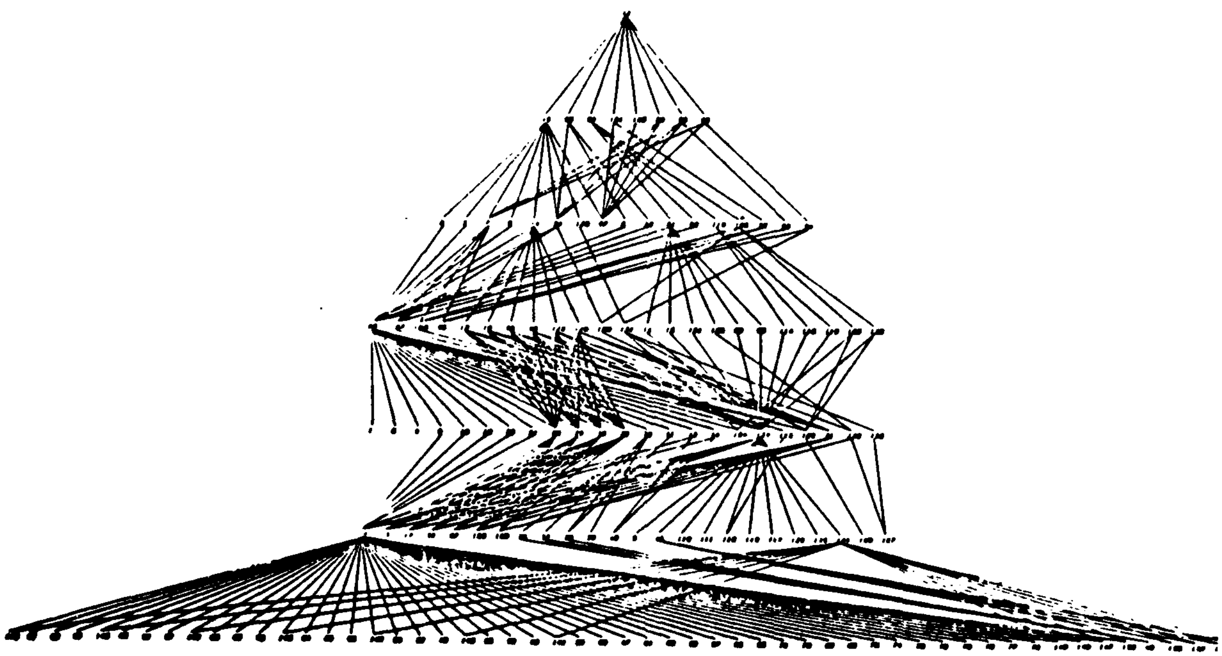


Figure II-4

The optimization-based approach used in MOLD provides a very natural way to overcome the limitations of the classical SE approach. MOLD uses an active constraint strategy to decouple system elements from one another. Changes in the coupling between design tasks occur naturally as various constraints come into play. MOLD is able to use efficient, reliable numerical optimization algorithms to search through alternative decouplings for complex design processes.

4. Limitations of the MOLD Computer Program

MOLD is currently based on the use of the generalized reduced gradient method for solution of the design optimization problems. A penalty function is used to quantify the sensitivity of changing the parameters that are passed between system elements. These methods essentially limit MOLD to dealing with continuous, rather than discrete, design alternatives and constraints. Although extensive comparisons are not available, it seems intuitive that a constraint-following technique might be more efficient than the penalty function approach for computing sensitivity information.

5. Conclusions and Recommendations

A system engineering approach to design is essential to achieving Project Forecast II *Objectives. The multilevel optimization* by linear decomposition tool will provide significant capability for designers to use SE methods such as decomposition and optimization in a rational and cost-effective manner to solve design problems requiring innovation based on experience.

MOLD provides a framework for designers to capture rules of thumb used to drive existing decompositions. MOLD also provides a reminder that new missions and technologies require re-evaluation of these relationships.

Research and development sponsored and performed by Lockheed-Georgia, USAF Labs, NASA, NSF, MIT, RPI, and other technology centers has produced several advances that promise to significantly enhance the applicability of MOLD. MOLD can provide a test bed to make these results available to designers and system engineers.

F. EXTENDED OPTIMIZATION--QUANTITATIVE AND QUALITATIVE TECHNIQUES

Optimization is a process of selecting alternatives to meet criteria. The optimization process presumes that quantitative or qualitative statements can be made regarding the suitability of the alternatives. An optimization algorithm is a method for conducting a systematic search through the alternatives to identify one or more preferred candidates.

The end product of a successful optimization process is not a design. Successful optimization results in the design team understanding the technical issues underlying the design problem, specifically trade-offs and risks. Any optimized designs that are developed are by products. The final design decisions are always made by the design team based on the understanding they have gained from the optimization studies.

In order to be successful, the optimization process must generate explainable results. This does not imply that all steps have to be performed manually, or even that each step must be transparent: the explanation of the process need not follow the same lines as the process itself. The optimization process should accumulate and organize information that contributes to the design team's understanding to the technical issues.

In order to support the design team's efforts to understand the technical issues, optimization should be interactive. The optimizer should first propose a solution to the design problem. (A statement of the design problem must be made by the designer--design specification languages are promising tools for accomplishing this.) Many algorithms for quantitative optimization use a strategy of concurrent search and approximation to explore a design space delimited by implicit constraints. A simple form of interactive explanation, which is feasible now, is to present these approximations to the user through a graphical interface. The user can trace these functional relationships back to the design specification to gain an understanding of how the critical aspects of the design concept interact with each other. A (conceptually) straightforward extension of this approach would allow the designer/user to substitute alternative approximations for those accumulated by the optimization algorithms--a kind of "what if?" analysis.

The interactive optimization environment provides the design team with tools for examining complex alternatives and arbitrating among conflicting requirements, if all the relevant considerations can be quantified. The integration of heuristic methods to handle discrete parameters and constraints is an evolutionary development [Ref. 18].

It seems clear that the ULCE decision support environment will demand techniques for addressing design considerations that are not readily quantified. Knowledge-based systems technology appears to offer the best chance of addressing qualitative optimization. Some interesting capabilities have been demonstrated to date that shed some light on the solution. Knowledge-based systems have been applied to the preliminary structural design of large buildings in the "HI-RISE" computer program by M. L. Maher [Ref. 14]. Maher developed a schema for representing the current state of the building design (essentially a design specification language with somewhat limited scope). A knowledge base of preliminary design rules is used to synthesize candidate designs that meet specified requirements. Maher's approach has the potential to be extended to handle soft constraints and best-first search.

The contrast between HI-RISE and quantitative optimization techniques is instructive. HI-RISE never considers any infeasible designs: in contrast, depending on the initial design, almost all the designs examined by a numerical technique may be infeasible. HI-RISE works backward from the requirements, eliminating alternatives by applying the design rules in its knowledge base. A numerical method requires that a "design" (vector of values for parametric design attributes) be selected and evaluated before the algorithm really starts to do any work.

A decision support environment that integrates knowledge-based qualitative design synthesis with numerical optimization would provide the essential capability needed for decision support for ULCE. A valuable step toward such a tool has been taken in the PAPER AIRPLANE computer program, developed under the direction of Dr. Antonio Elias at MIT [Ref. 8], and the RUBBER AIRPLANE computer program being developed by Mark Kolb of MIT [Ref. 13]. PAPER AIRPLANE represents engineering knowledge about conceptual aircraft design in the form of numerical constraints. Constraint propagation [Ref. 6] is used to find a set of consistent values for all the design attributes. RUBBER AIRPLANE adds to this capability a representation of the design in terms of components and models. RUBBER AIRPLANE also can use numerical optimization to resolve tough constraint propagation problems involving multiple simultaneous constraints. The extension of this approach to include qualitative constraints such as those addressed in HI-RISE offers significant potential for advancing ULCE objectives.

G. ARBITRATION AND NEGOTIATION METHODS AMONG COMPETING DESIGN REQUIREMENTS

1. Introduction

Engineering designs are often the result of the joint efforts of many engineers representing a variety of disciplines working to create an optimal design. This involves two levels of optimization, one of which has largely been ignored because of its inherent qualitative nature and the constraints of internal politics in engineering organizations.

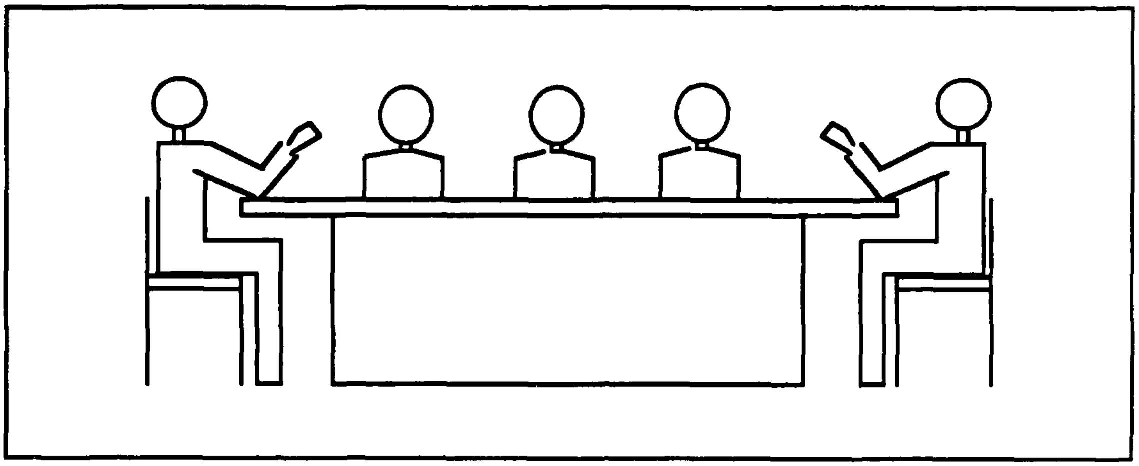
Existing design optimization techniques focus on numerical optimization of objective functions of design parameters [Ref. 23]. Such techniques, however, are limited to readily quantifiable objectives and generally are used within a single engineering discipline. An entirely different level of optimization occurs when a number of engineering disciplines must interact and where some objectives are qualitative in nature. This is a process of negotiation and trade-off that is not generally recognized as an integral part of design optimization. Little attention has been given to developing improved methods of negotiated optimization.

This paper proposes approaching the second type of engineering optimization through decision theoretic methods from game theory and operations research [Refs. 21, 12, 22] and through an adaptation of expert system methods [Ref. 16] for the representation of specifications, objectives, design rules, and optimization guidelines. Such an approach can provide the basis for future development of more complete heuristic/ algorithmic optimization systems.

2. Life Cycle Engineering

True optimization in engineering design must take into account all important aspects of a product's life cycle from its initial definition to its final scrapping. Today, however, the typical design process is linear and sequential with the design being "thrown over the wall" from one design group to the next. In some cases, there is more feedback and parallelism in the process with a formal design review board consisting of representatives from the various engineering disciplines. There is an interaction and negotiation among these designers in an attempt to optimize the design (Figure II-5). The effectiveness of these negotiations is problematical (Figure II-6), in part because the design may be partially or entirely complete and because some disciplines may be in a weak negotiating position. There is the additional difficulty in that the engineering disciplines do not have thoroughly developed metrics for evaluating the design. A solution requires real-time, on-line methods for representing specifications and objectives, reviewing the design status, evaluating the design, suggesting revisions, and making trade-offs between the competing aims represented by the different engineering disciplines.

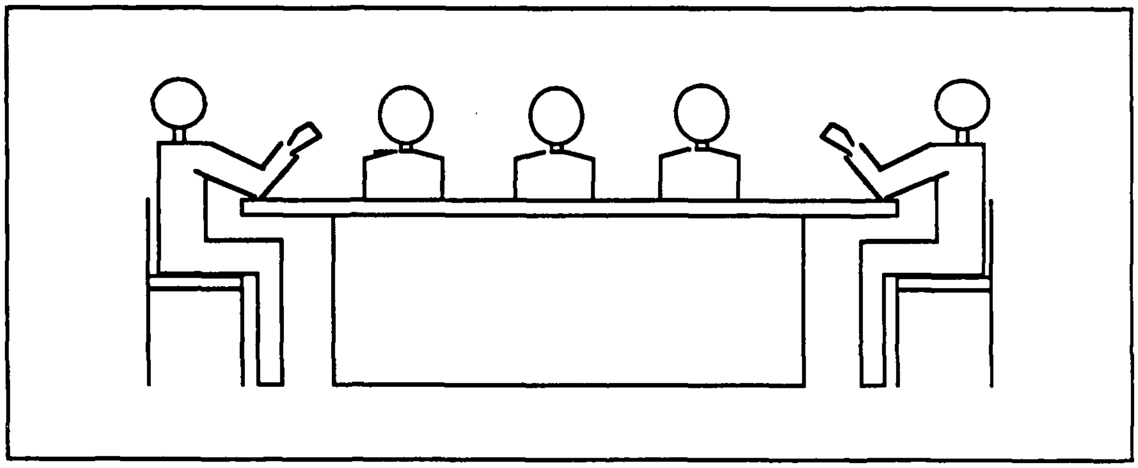
Design itself is often seen as a component in a linear, sequential process of the life cycle of a product. Other components may include specification, conceptual design, preliminary design, detail design, manufacturing planning, tool design, manufacturing, operation, and maintenance (Figure II-7). However, a more realistic approach to the



Advantages:

- Group creativity
- Unrestricted communication
- Rapid feedback

Figure II-5. Design Negotiations - Advantages



Disadvantages:

- Untimely for design revisions
- Personality dependent
- Imprecise analyses
- Time pressure in meeting

Figure II-6. Design Negotiations - Disadvantages

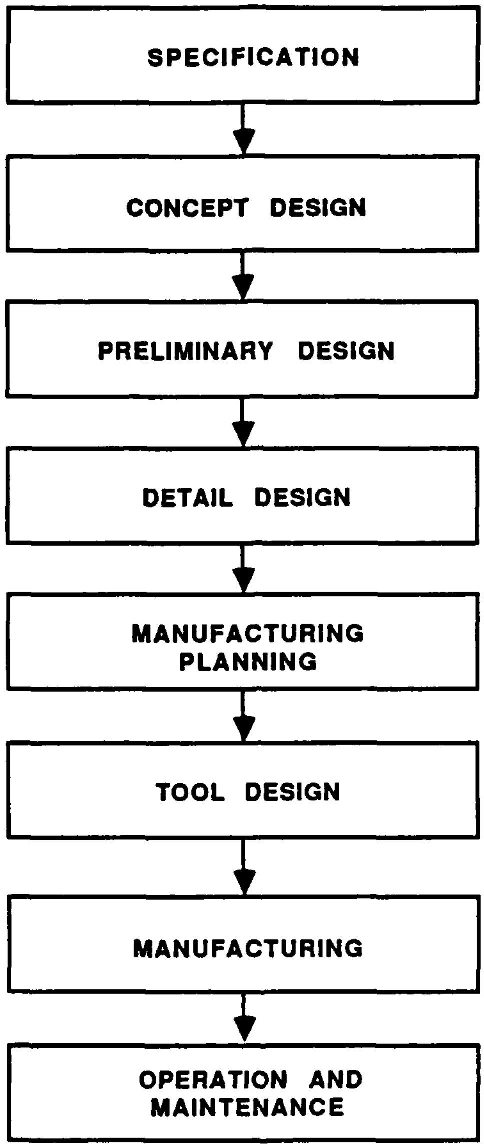


Figure II-7. Product Life Cycle - Linear View

product's life cycle is to take an organic view (Figure II-8) which recognizes that specification and design are central to the entire life cycle process. The organic view is essential for a proper perspective on design goals and, consequently, on the evaluation, trade-off, and optimization process.

The organic view of the product life cycle is the basis of an emerging discipline called life cycle engineering. Life cycle engineering is an approach that guides engineers toward designs that are optimized with respect to a wide range of goals such as mission

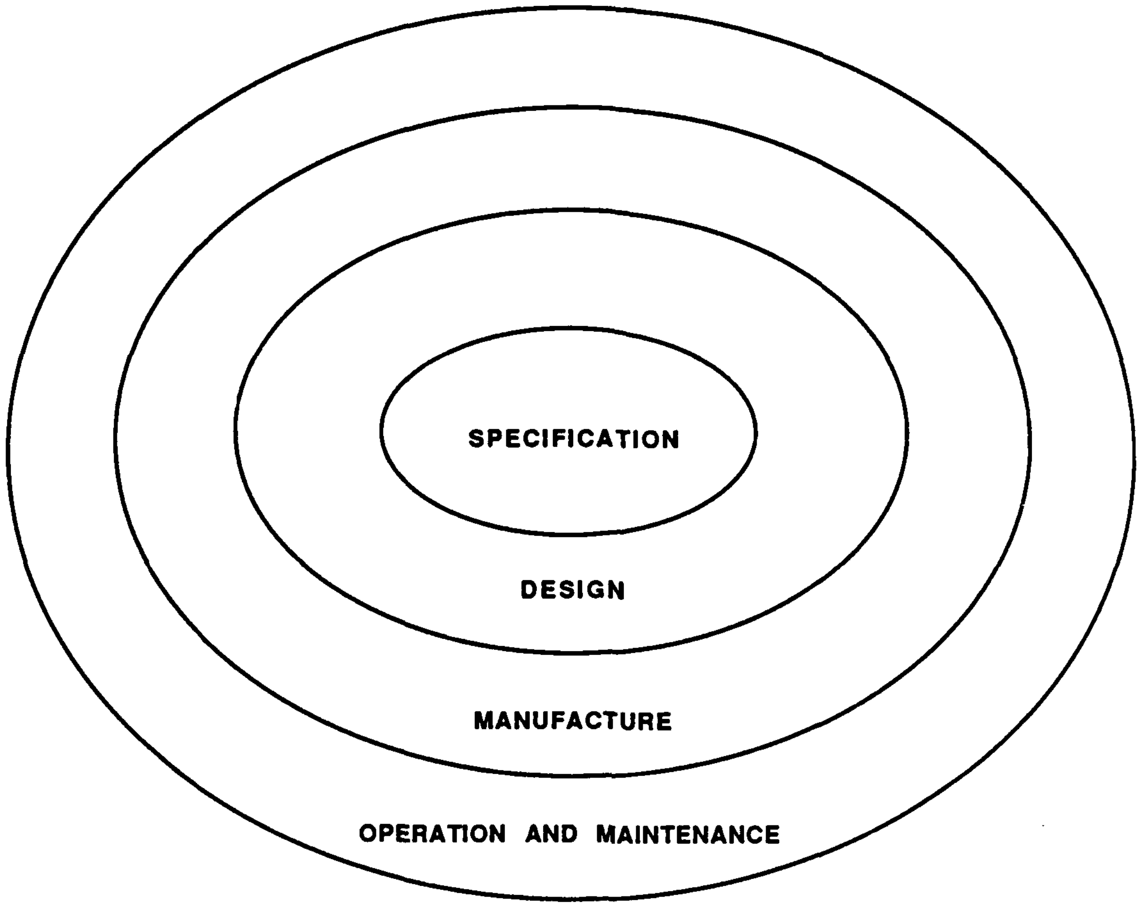


Figure II-8 Product Life Cycle - Organic View

completion capability, performance, reliability, maintainability, producibility, aesthetic quality, marketability, and others. Engineering design optimization in such a heterogeneous, multivariable, and sometimes ill-defined environment requires corresponding multidisciplinary efforts to create new design methodologies. Of necessity, these will draw on mathematics, engineering, and computer science.

3. Negotiation vs Numerical Optimization

a. Utility Functions vs Objective Functions

The two levels or types of design optimization can be identified as negotiation and numerical optimization. There is a large body of research literature on the methods of numerical or mathematical optimization. In general, these methods depend on the formulation of a quantitative objective function of design parameters and an accompanying quantitative, mathematical description of constraints.

Many aspects of designs are not easily quantifiable and, thus, lend themselves more readily to approaches from game theory and decision theory utsing utility functions [Ref. 22]. Utility functions can be used in design to serve as measures of the payoff or utility of a particular design. Some components of *design utility functions* (see Evaluation metrics below) may be calculated directly from design parameters as with objective functions. Other components, however, may be more subjective and be based on the judgment of the designer or group of designers. This gives design utility functions greater flexibility and a wider range of applicability than allowed by objective functions. In particular, there is a natural and elegant way in which design negotiations and trade-offs between design groups represent different design goals.

b. Direct Mulitlateral Bargaining

Direct multilateral bargaining is a method whereby an optimal agreement can be reached among two or more individuals or groups with differing interests [Ref. 12]. The following is an adaptation of this method for the case of design trade-offs.

Let

A = a provisionally agreed on design in the space of feasible designs

A' = a revised design

$u_i(a)$ = the design utility function measuring the quality of design A from the point of view of engineering group i with

$0 <$ or $= u_i(A) <$ or $= 1$ for all i (Eq. 1)

N = number of engineering groups participating in the bargaining

w_i = weighting factor assigned to engineering group i with

sum $[w_i] = 1$, $i = 1$ to N

$S(A)$ = weighted sum of utility functions for design A:

$S(A) =$ sum $[\{w_i\}\{u_i(A)\}]$, $i = 1$ to N (Eq. 2)

The tradeoff criterion is given by

$S(A') > S(A)$ (Eq. 3)

The basic rule of direct multilateral bargaining is that any design group may offer a revised design, A', if Eq. 3 is satisfied, and then all groups must accept A' as the new provisionally agreed on design, A.

The choice of a weightrd sum, Eq. 2, of utility functions as the basis of comparison of design needs some justification. There are three major alternative candidate methods for dealing with the utility functions to yield a measure of the overall quality of the design:

The product

$$\mathrm{Prod}_i\,[u_i\,(A')] > \mathrm{Prod}_i\,[u_i\,(A')]\quad,\quad i = 1 \text{ to } N$$

Maximin

$$\max \min_i u_i\,(A') > \max \min_i u_i\,(A)$$

(weighting factors may be used)

Limited Maximization

$$\max_i u_i\,(A') > \max_i u_i\,(A) \quad \text{with } u_j\,(A') > \text{or} = u_{jo}$$

for all j not equal to i, where u_{jo} is a fixed minimal value of $u_j(A')$ (weighting factors may be used).

Each of the four methods (i.e., weighted sum, product, maximin, and limited maximization) has its advantages and disadvantages.

The weighted sum is conceptually the simplest and best meets our criteria that the system should be easy to understand. For any engineering design-decision support system to be accepted and profitably employed by an engineering design organization, both the trade-off criteria and the weighting factors must be easily understood.

The product and maximin tend to equalize the u_i by exaggerating the importance of the worst u_i. Similarly, limited maximization exaggerates the importance of one u_i. This is true, notwithstanding the fact that limited maximinization may be cascaded down a series of variables. Maximin does allow visibility to the group with the lowest u_i. The product even gives veto power to any group. The difficulties can be partially alleviated by the introduction of weighting factors. However, weighting factors for the product, maximin, and limited maximinization have their own attendant drawbacks, the main problem being that the effects of the weighting factors are not immediately and intuitively obvious. This complicates the assignment of weighting factors and makes the whole process less readily understandable.

A robust design-decision support system might provide flexibility in which of the four methods will be used for combining the utility functions. The weighted sum method is discussed in the following section.

c. Assignment of Weighting Factors

The weighting factors can be formulated so that they are normalized, summing to unity. The assignment of a relative weight to the utility function representing a design discipline is obviously an important issue. There are three major sources to be looked to for guidance on the assignment of weights.

First is the customer. If the customer has a clear idea of what he wants and the relative importance to him of the different ways to evaluate a design, then he could, in principle, specify a weight vector. An example is DoD specifying that performance, cost, schedule, supportability, and producibility will be considered equally in design evaluations.

The second source for selecting a weight vector is engineering management. This could be the project manager or other officer above or outside the design groups. Based on his experience and the customer specifications, he can decide on a weight vector.

The third source is the design groups themselves. There are at least two ways the design groups could assign a weight vector. One is by face-to-face negotiations in the light of the design specifications. A second method is by voting. Each design discipline decides on a weight vector assigning relative weights to all the other design disciplines and leaving out their own. These weight vectors are then averaged and normalized, resulting in a composite weight vector incorporating the views of each discipline as to the relative importance of all the other disciplines.

4. Design Specifications

Design specifications can be conveniently and naturally divided into three classes [Ref. 15]. The first is the class of *hard constraints* that must not be violated. An example in aircraft design is a minimum range. If the hard constraint is violated, then the metric or utility function becomes negative, i.e.,

$$u < 0 ,$$

so that Eq. 1 is no longer satisfied.

The second class is that of *soft constraints*, which are target or threshold values that are not absolutely required for the success of the design, but would enhance the design if they were met. An example of a soft constraint in automobile design is a target value of miles per gallon.

The third class of specifications is that of *objectives*, which are quantities to be maximized or minimized. An example of an objective is to maximize reliability.

Soft constraints and objectives are candidates for optimization techniques and trade-off negotiations. In many cases, however, just meeting the hard constraints is difficult enough. But even with the hard constraints there are problems of optimization connected with allocation of design requirements such as reliability from the system level down to the component level.

5. Evaluation Metrics

A basic element of the decision support system is the set of metrics or measures of effectives (MOE's) for design evaluation [Ref. 11]. Rather than being absolute quantitative measures of the quality of the design, the metrics are used to compare alternative designs. The metrics provide the compass to direct the designers and the decision support system in navigating through the space of all possible designs.

Each design group or discipline must be responsible for devising metrics to give comparative, quantitative measures of the goodness of the design from their own partial viewpoint. The creation of such metrics is, in itself, a nontrivial task. Metrics need to be general enough to handle the entire class of designs. In practice, only a subset of the complete metric will be applied to any particular design. Furthermore, a useful metric will measure three classes of specifications discussed above in the section on design specifications. Historical data on existing designs can be used to test the matrices to see how well they distinguish the qualities of designs. With the help of the decision support system the various metrics are combined to yield a measure of the overall quality of the design.

The most difficult problem in devising a system of metrics is to ensure consistency, among the various design groups, in how a value is assigned to each metric, and thereby avoiding the consequences of *Arrow's Impossibility Theorem* [Ref. 7] which relates to the difficulty of group decision making. There must be a scheme of normalization [Ref. 15] so that each group's metric is cardinal rather than ordinal (see Section II.A.), thus allowing the several metrics to be combined. One simple approach is to begin by assigning 0 to the minimal level of meeting specifications and 1 to the "best possible design" for each discipline.

6. Conclusion

The implementation of a decision support system for design negotiations has a good probability of yielding significantly beneficial results. The first steps toward this will require research and experimentation with a prototype system.

H. DESIGN ADVISORY SYSTEMS

1. Introduction

The advancing state-of-the-art in expert systems, intelligent user interfaces, object oriented programming methods, and more powerful computer hardware is making possible some promising new approaches to design support, which can be collectively called design inventory systems. Early forms of such systems have been used for over a decade, but advancing techniques are taking these systems to a new level of effectiveness. The best ideas are still on the drawing boards or in the laboratories and need further research and development. In this paper a brief overview is presented of some of the more important capabilities to be looked for in design advisory systems.

2. Translation of Customer Specifications into Design Requirements

Automated expert advice and guidance in the process of translating customer specifications into design requirements is an important area because it sets the stage for the entire product life cycle. This area includes the capability to allocate requirements according to the physical and functional hierarchies.

3. Design Rule Subsystem

Some existing CAD/CAE systems currently have the capability to allow users to input design rules that are then utilized in various ways.

4. Design Review and Checking

This incudes checking conformance to standard company specifications and to design specific requirements, as well as functional checks.

5. Design Guidance

An advisory system can be of use to designers who wish to draw on a rule base of expert design guidelines. This is particularly important in a multidisciplinary environment, such as ULCE, because expertise from outside the designer's own discipline can be brought to bear.

Furthermore, rule base design guidance could be used to produce candidate solutions to design problems.

A third method of design guidance is to have the system point out to the designer the weaknesses in the design and make specific suggestions for improvements. Such systems have already been built and are in use.

6. Component and Material Selection

A rule-based system can query a component or material data base to retrieve a set of suitable candidates for use in the design.

7. Decision Rationale Audit Trail

This provides for tracibility of design decisions back to the original rationale. It consists of a journal or record of how the design was accomplished, what analyses were completed, why certain trade-offs were made, etc.

8. Representation of Design Hierarchies

These include the physical hierarchy (system-subsystem structure) and the functional decomposition (used in requirements allocation). An intelligent, interactive representation of these hierarchies can show designers where they are working in the overall scheme and provide a picture of the status of the design.

9. Engineering Knowledge Representation For Design Optimization

The manner in which engineering knowledge and data are represented in a computerized design optimization system in the ULCE environment is extremely important. One of the major difficulties facing implementation of optimization techniques in the ULCE environment is the popular impression that only an expert in optimization can apply optimization techniques. The representation scheme must provide assistance to the engineer who is not well-versed in optimization. There are so many different optimization techniques that it is impractical for an engineer to be familiar with all of them and know which one is best for his particular problem. Furthermore, the engineer must formulate his design problem in a manner consistent with the optimization method employed and may need guidance in this. Finally, the results of the optimization algorithms and the relationships between competing goals must be presented in a readily intelligible fashion to allow the engineer to effectively proceed with interactive tradeoff and redesign. Research is needed to create ways to present guidance and feedback in the optimization system.

10. Optimization Algorithm Selection

This is a rule-based methodology for selecting the most efficient optimization algorithms for the particular problem being considered.

11. Knowledge-Based Guidance For Optimization Problem Formulation

This is a further aid to the engineer in making use of mathematical optimization. It guides him in setting up his problem in a format amenable to optimization routines. Another use, though more difficult, is to assist the engineer in choosing the right problem to solve.

12. Interactive Trade-off and Redesign Methodology

This type of design support would give the engineer rapid feedback on "what if" games for design trade-offs. Object oriented design data bases can be useful in this regard because of the natural way in which relationships within the design can be represented.

13. Conclusion

As the design process becomes more demanding and skilled engineers become rarer and more expensive, design advisory systems will need to become more robust. This is an area in which systems research would be highly leveraged in terms of its potential payoff.

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Appendix A

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Keynote Speaker at Initial Working Group Meeting

Colonel Donald Tetmeyer
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Appendix B

WORKING GROUP MEETING AGENDAS

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WORKING GROUP MEETING AGENDAS

The DSS Working Group held two meetings, a one-day meeting at IDA on April 21, 1987, and a one and one half day meeting at IDA on May 19 and 20, 1987. A follow-up meeting by IDA members of the working group was held at IDA on May 27 to finalize the R&D plan recommendations. Agendas for the first two meetings are included in this appendix.

DSS WORKING GROUP MEETING NUMBER 1

21 APRIL, 1987

AGENDA

0830	Welcome and Announcements - William Cralley, IDA
0845	Keynote Address - Colonel Donald Tetmeyer, AFHRL
0915	Working Session - Definition of the Scope of ULCE
1030	Break
1045	Working Session - Design Optimization in the Context of ULCE
1200	Lunch
1300	Working Session - Refinement of ULCE DSS Scope and Requirements
1430	Break
1445	Identification of R&D Areas relevant to ULCE DSS Problems
1600	Call for Volunteers for White Papers on R&D Areas
1630	Determination of Date and Place of Next Meeting
1640	Adjourn

DSS WORKING GROUP MEETING NUMBER 2

MAY 19-20, 1987

AGENDA

May 19

0900 Welcome and Announcements -- William Cralley, IDA

0915 Presentations by members of the group on white paper topics

Scope of ULCE -- Dave Owen, IDA

Theory of Measurement -- Bob Kuenne, Princeton University

1030 Break

1045 Continuation of presentations and discussion

Applications of Pattern Recognition to ULCE -- Iman Foroutan, Hughes

Propagation of Design Changes -- Iman Foroutan, Hughes

Information Modeling Issues and Human Interface Requirements --
Michael Wozny, National Science Foundation

1215 Lunch

0115 Continuation of presentations and discussion

Decomposing the Design Process -- Ed Rogan, Lockheed-Georgia

Arbitration and Negotiation, Design Advisory Systems --
Joseph Naft, University of Maryland

0245 Break

0300 Continuation of presentations and discussion

Integration of Software and Hardware Design -- Dave Dierolf, IDA

Multiobjective Optimization Methods -- Bob Kuenne, Princeton University

0400 Discussion and Homework Assignments on Ranking of R&D Areas

May 20

0830 Presentation of Rankings of R&D Areas by Working Group Members

0930 Discussion of Rankings

1000 Break

1015 Development of Consensus Recommendations

1145 Wrap up

1200 Lunch, discussions

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